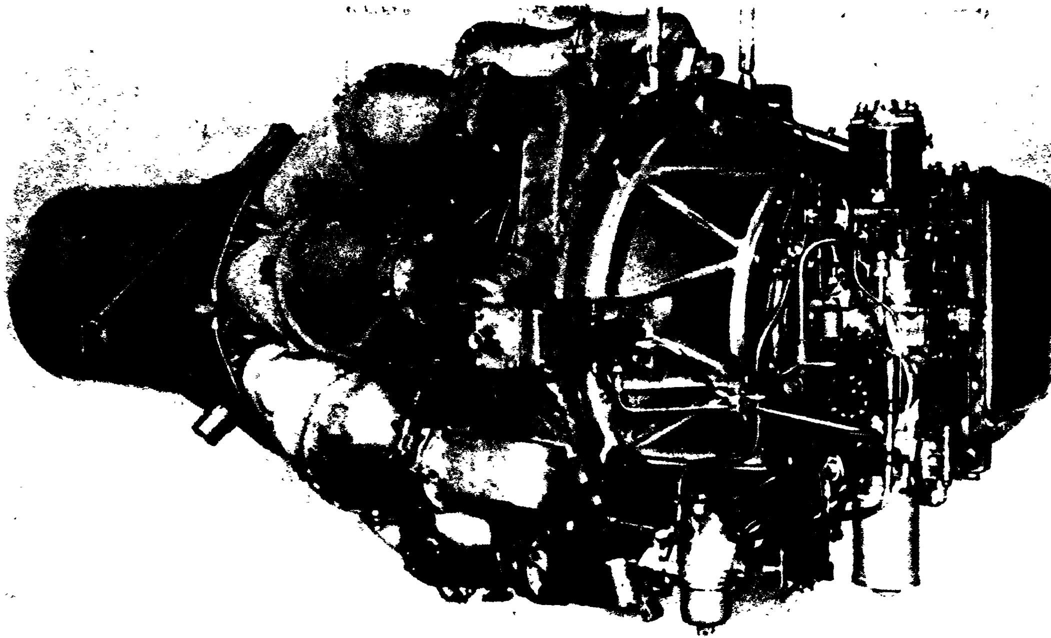
AERO ENGINES FOR STUDENTS

Including Gas Turbines



Frontispiece

ROLLS-ROYCE DERWENT V TURBO-JET ENGINE *By courtesy of Rolls-Royce Ltd.*

Static Thrust 4,000 lb., Weight 1,250 lb. (The Gloster Meteor with two Derwent engines set up a new speed record of 616 m.p.h. on September 7th, 1946)

AERO ENGINES
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Including Gas Turbines

by

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PREFACE

This book is written for the serious student who is already familiar with the elementary principles of the internal-combustion engine.

The scope of the book and the manner of its arrangement has been governed by much experience in the training of aeronautical students, and the information given is therefore well adapted to the needs of all those who desire to supplement their existing knowledge of the subject.

Although supercharging is of the utmost importance when concerned with the performance of aero engines, experience has demonstrated that in general both students and those concerned with engine maintenance have very little knowledge of the various aspects connected with the operation of such a device. For this reason the factors influencing the supercharging of engines have been explained in a progressive manner, and in consequence readers are enabled to understand the reasons underlying the development of the two-speed, the two-stage and the turbo-supercharger.

In a book intended for students the illustrations are of great importance, and therefore these have been carefully chosen in order that they may convey the maximum amount of information. In this repect the author is greatly indebted to the various manufacturers and others who have made this feature possible by supplying photographs and line drawings. Acknowledgment has been made on the individual illustrations.

R. A. BEAUMONT

PREFACE TO SECOND EDITION

In consequence upon the release of information in the post-war period a thorough revision of the book has been made. The majority of the ninety-nine illustrations contained in the first edition have been changed and additions also made to include the most modern piston engines and, that "revolutionary" product of British engineering genius—the gas turbine.

These new and additional illustrations (which include features of the American Wright Cyclone engine), have been incorporated in the knowledge that good illustrations convey essential information of the functioning or assembly of components that is not readily obtained by reading text. The special feature of this book has been therefore augmented in the new edition. The writer is again most grateful to the manufacturers and others who have made this possible by their generous assistance.

Considerable re-arrangement and additions have also been made to the text; a new chapter on the Gas Turbine has been included, and details of the modern Injection Carburettor appended to Chapter V.

Finally, I would like to thank those readers of the first edition who have written to me in appreciation. It has been my endeavour to make this edition a more worthy successor.

R. A. BEAUMONT.

CONTENTS

CHAPTER I

Factors Influencing Design

In order to appreciate the construction of the most highly developed form of internal-combustion engine—the aero engine—it is necessary to have some knowledge of the factors which influence its design.

WEIGHT/POWER RATIO

Whatever type of engine may be considered, its weight/power ratio is of primary importance. The power output for a given weight must obviously be as high as possible in order that the greatest amount of useful power is available for either achieving maximum speed, load carrying capabilities, or a combination of both. The dead weight of the engine has to be carried by the aircraft, and the greater the power available for this weight the better will be its performance.

The modern high performance aero engine has reached such a stage of development that it weighs little more than 0.8 lb. per brake-horse-power at the special rating for take-off conditions (see Table I).

The power per cubic inch (or per litre), which is often quoted should be regarded as a measure of performance only for engines of like capacity as this ratio decreases as cylinder dimensions increase. For a given piston speed, the b.h.p./litre is in fact inversely proportional to the cylinder bore for engines whose cylinders are geometrically similar. The power per sq. in. of piston area is more usually taken as a criterion of engine performance.

A simple calculation will show that, due to the area varying as the square of the diameter, a scaling of the dimensions with a given power per sq. in. of piston, will result in the inverse proportion mentioned above. For example, with two similar cylinders, of 6 in. by 6 in. and 3 in. by 3 in. bore and stroke respectively, the piston area of the larger will be four times that of the smaller, but its swept volume will be eight times larger. Thus there will be a fourfold power increase but the power per unit capacity will be halved.

A graphical survey of the manner in which the power per sq. in. of piston area has steadily increased while the weight per h.p. has decreased is given in Fig. 1 which represents the development of "Bristol" air-cooled radial engines.

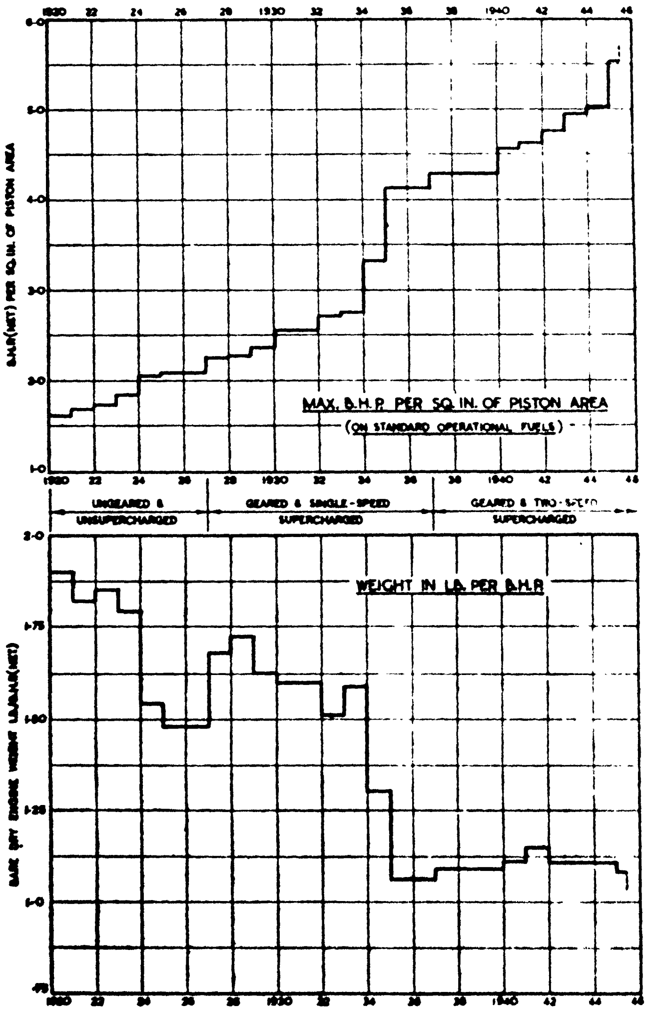


FIGURE 1 *By courtesy of The Bristol Aeroplane Co. Ltd.*

DEVELOPMENT OF "BRISTOL" AIR-COOLED RADIAL ENGINES

It must not be thought that the problem of achieving high power for low weight is only concerned with making the engine components as light as possible. For reasons of structural reliability it is very difficult to reduce the weight of the main components, such as cylinders, crankshaft and connecting-rod assembly, and the problem resolves itself into increasing power output by other means without increasing weight in the same proportion. The number, disposition and type of cylinders, compression ratio, crankshaft speed, supercharging, etc., are all factors contributing to the most efficient generation of power.

The very considerable advance made in developing the high-strength steels and light alloys used in the construction of aero engines has contributed largely to the steady decrease in the weight/power ratio.

CYLINDERS

Although the number of cylinders is dependent upon the required power output, it is generally more efficient to use a larger number of smaller cylinders than to obtain the power by using a few of larger capacity. With small cylinders a higher rotational speed of the engine is possible, due largely to the shorter stroke and to the use of smaller and thus lighter pistons, which reduce the inertia forces. These forces are due to the acceleration and deceleration of the piston during the stroke and become very considerable at the maximum speed of the engine.

Air-cooling of small cylinders also presents an easier problem, particularly on a multi-cylinder in-line engine. The radial type engine in which all cylinders face the cooling air stream is able to use larger cylinders, but for high powers needs two or more rows, staggered in relation to each other.

One decided advantage of using a large number of cylinders is the resulting smoothness of running due to the short interval between successive power strokes. All engines operating on the four-stroke principle have as many power strokes in each two revolutions of the crankshaft as there are cylinders,

consequently a 24-cylinder engine could have a power impulse every 720/24=30 deg. rotational movement of its crankshaft.

The number of valves will be influenced by the size of the head, so that to avoid restriction at the inlet and exhaust ports which will lead to undue fall in power at high speeds, the valve port areas will govern the minimum size of cylinder.

To overcome the disadvantage of restricted port area and to entirely dispense with the normal poppet valve and its method of operation, the sleeve-valve engine was designed. Particulars of this engine will be given subsequently.

CRANKSHAFT SPEED AND REDUCTION GEARING

The crankshaft speed of an aero engine is necessarily high in order to develop the maximum possible power output. With regard to crankshaft speed, do not compare speeds of engines which have different strokes. It is the mean piston speed which is a limiting factor as regards power output. For example, an engine with a 3-in. stroke running at 6,000 r.p.m. would have the same mean piston speed as another with a 6-in. stroke running at 3,000 r.p.m.

The mean piston speeds of aero engines at present are of the order 2,500—3,000 ft. per min.—up to 34.1 miles per hour —after stopping every 6 in. or so, according to the particular stroke.

The crankshaft speeds of these engines are from 2,500—4,000 r.p.m., and in general these speeds are too high for the maximum propeller efficiency (i.e., the maximum transfer of engine power to forward thrust), so that reduction gearing is interposed between the crankshaft and propeller shaft, the reduction ratio being approximately 0.5 to 1.

The type of reduction gearing is dependent upon the type of engine, the radial engine using an epicyclic arrangement whereby the axis of the propeller shaft is in line with that of the crankshaft (Fig. 2), this being necessary in order to maintain an even airflow over every cylinder. A similar axial arrangement is also adopted on the six-cylinder in-line geared Gipsy Queen 71 engine.

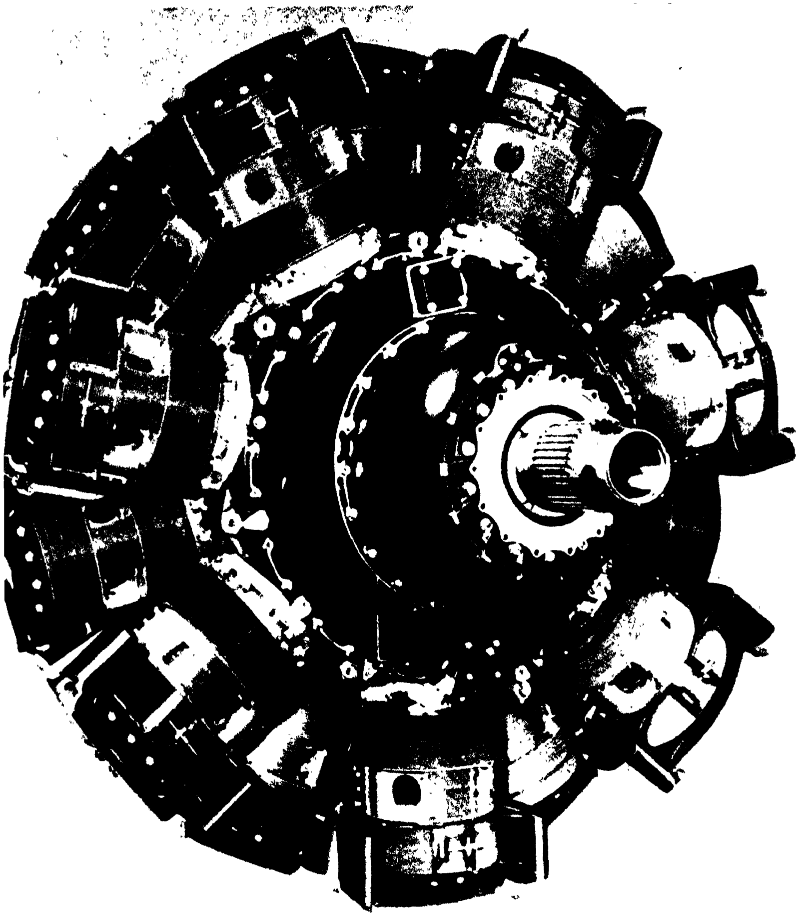


FIGURE 2 *By courtesy of The Bristol Aeroplane Co. Ltd.*

"BRISTOL" HERCULES 100-SLEEVE-VALVE ENGINE

The layshaft type of gear is more simple, and is generally used on in-line liquid-cooled engines, the axis of the propeller shaft being parallel to that of the crankshaft. This layout is typical of the Rolls-Royce Merlin and Griffon engines. With twin crankshafts and compound reduction gearing as used on the Napier Sabre the design is more complicated.

COOLING

Engines may be classified according to the method by which they are cooled, i.e., air-cooled or liquid-cooled, the former being normally used for in-line engines of moderate power output and for large radial engines, whilst the latter is employed for the high-power Vee-type engine.

The term liquid-cooled is used because modern engines do not use water alone as the cooling medium, but a mixture of water and ethylene glycol, which has much more suitable characteristics.

With water only, the boiling point is the limiting temperature, but in practice it is of course necessary to always maintain a safe margin of 15 to 20 deg. C. under the boiling point. As the boiling point of water decreases with altitude, due to the diminished atmospheric pressure, water cooling is not practicable for high altitude flying, neither is it suitable for cold climates owing to freezing when the engine is stationary. The ethylene glycol water mixture, however, has a much higher boiling point and a lower freezing point, the former making it possible to use a higher water jacket temperature, which leads to better operating efficiency, and the latter enables the engine to operate in colder climates without the need for draining the liquid when the engine is not running. It is also possible to use a smaller radiator with the high temperature coolant.

The liquid-cooled Vee engine, of which the Rolls-Royce Merlin and Griffon are types, have a small frontal area for their power output and are consequently very suitable for low drag installations in aircraft.

Although the radial engine has a large frontal area, the modern systems of cowling greatly reduce the drag (air resistance) while giving adequate control of engine cooling, and as there is no radiator the total power plant drag does not differ materially from that of the liquid-cooled type.

With either type it is necessary to provide sufficient cooling to cater for climbing under greatest power conditions when the forward speed is relatively low and engine cooling

requirements are severe, and provide means for maintaining the desirable temperature at cruising speeds when power output is much reduced.

The air-cooled type has controllable exit " gills " (Fig. 3) fitted to its special cowling which regulate the amount of air passing the cylinders, and the liquid-cooled engine has a radiator situated in a tunnel, through which passes a controllable air flow.

SUPERCHARGING

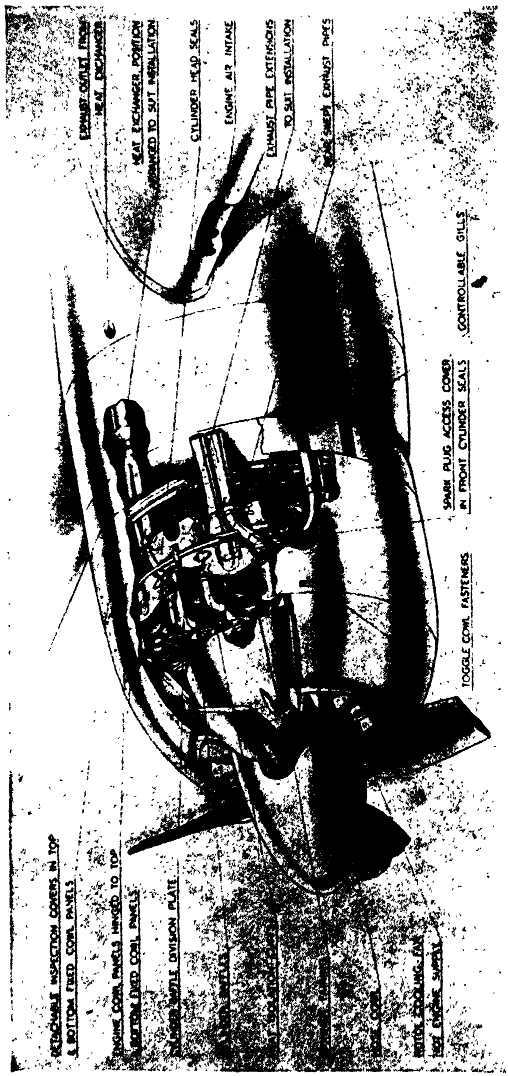
All high-power output engines are fitted with a supercharger, which is a device for obtaining a greater weight of charge in the cylinder during induction than is possible with the normal induction system. The advantages obtained are greatly increased power output both at ground level and at all altitudes of operation over that possible with a normally aspirated engine of equal capacity (whose full throttle power output steadily decreases as altitude increases). This increased power output is naturally accompanied by an additional amount of heat, which must be dissipated. The engine must, therefore, be structually strong enough to withstand the increased power without loss of reliability, and the cooling system must be adequate to cater for the additional heat generated and ejected from the exhaust. As the supercharger can cause damaging powers to be developed in the engine at or near ground level, automatic devices are necessary to control the degree of supercharge.

Further aspects of supercharging will be considered later when dealing with the constructional features of this device.

In conjunction with supercharging, a form of power boosting using methanol-water mixture injection has now been sucessfully operated, and this aspect will also be discussed in Chapter IV.

THERMAL EFFICIENCY

The thermal or heat efficiency of an engine is the ratio between the amount of heat which is converted into useful work, i.e., the brake horse-power, and the amount of heat



By courtesy of The Bristol Aeroplane Co. Ltd.

FIGURE 3

"BRISTOL" CENTAURUS ENGINE INSTALLATION WITH REAR SWEPT EXHAUST SYSTEM FOR MULTI-ENGINED AIRCRAFT

liberated by the complete combustion of the fuel supplied, and when calculated on the basis of brake-horse-power it is referred to as brake thermal efficiency.

This efficiency is important, as the higher the ratio the less becomes the fuel consumption for a given power, and fuel economy is an essential requirement for an aero engine.

When reading about four-stroke engines of, say, 1,000 b.h.p., it is not generally realized that this 1,000 b.h.p. only represents about 28 per cent of the total heat energy available on complete combustion of the fuel in the engine cylinder. In other words, the equivalent of 2,570 b.h.p. is lost if 1,000 b.h.p. is available as power output. This loss is chiefly due to heat ejected during the exhaust strokes (which in itself is far greater than the power developed) and that lost to the cooling medium. A better picture is given of the amount of heat ejected to exhaust, assuming 1,000 b.h.p. output, by stating that it is sufficient to bring to boiling point approximately 39 gallons of water every minute, the water commencing at 15 deg. C.

In order to achieve high thermal efficiencies it is necessary to use a high compression ratio in the engine cylinders, but a ratio is soon reached which causes a very unstable form of combustion called detonation in which a wave of high pressure travels through the combusting charge. This causes exceptionally high pressures to be generated and damaging stresses to be transmitted to the engine structure.

Excess supercharging can also bring about detonation, so that the compression ratio chosen has to be a balance between the requirements of the high power output obtained through supercharging and the fuel economy resulting from a high compression ratio. An average ratio is about 6.5 to 1.

CARBURATION

Unlike the automobile carburettor, which is normally designed for ground level atmospheric conditions only, the aero engine carburettor must be able to adjust itself to the varying atmospheric conditions due to change in altitude of the aircraft.

An important consideration in this respect is the automatic control of mixture strength, which, if not controlled, will become progressively rich due to the less *weight* of air drawn through the carburettor as the atmospheric pressure decreases with altitude.

This effect is due to the fact that at any given throttle opening and r.p.m. the same *volume* of air is being drawn into the engine, thereby maintaining the discharge of petrol from the jets constant, but as the altitude increases and the atmospheric pressure drops, this same volume will weigh progressively less and the balance between weight of air to weight of petrol will be upset.

This alteration in mixture strength, if unchecked, would very seriously affect engine running as well as fuel economy, and in consequence automatic devices have to be fitted to take charge of these conditions.

Due to the varying degrees of supercharge, it is also necessary for the carburettor to supply varying mixture strengths to cater for these conditions in addition to the control for altitude. Another special condition is the provision of ultra-weak mixture strengths for cruising conditions at part throttle openings.

Ice formation at the carburettor throttle due to altitude atmospheric conditions is another problem which is peculiar to the aero engine, and provision has to be made to overcome this.

The construction of the actual carburettor and details of the special controls fitted will be explained and illustrated later.

ACCESSORIES

The modern aero engine, in addition to fulfilling its primary function of providing the power to drive the propeller has also to act as a miniature power station, supplying power for the actuation of a variety of mechanisms associated with itself and with the aircraft. There are fuel and oil pumps, tachometer drives, hydraulic pump for actuation of retractable undercarriages, etc., air pump for wheel brakes, electrical

generator, suction pump for operation of turn indicator and directional gyro. Previous practice was to group most of these accessories on the rear cover but, in present high power designs the accessories for aircraft services are grouped on a separate gear-box which is attached to the aircraft bulkhead, and shaft driven from the rear cover. In this way the design of the rear cover and drives is simplified, maintenance is facilitated and accessories non-essential to the engine operation are not so subjected to engine temperatures. The rear cover layout of a "Bristol" Hercules engine is illustrated in Fig. 4.

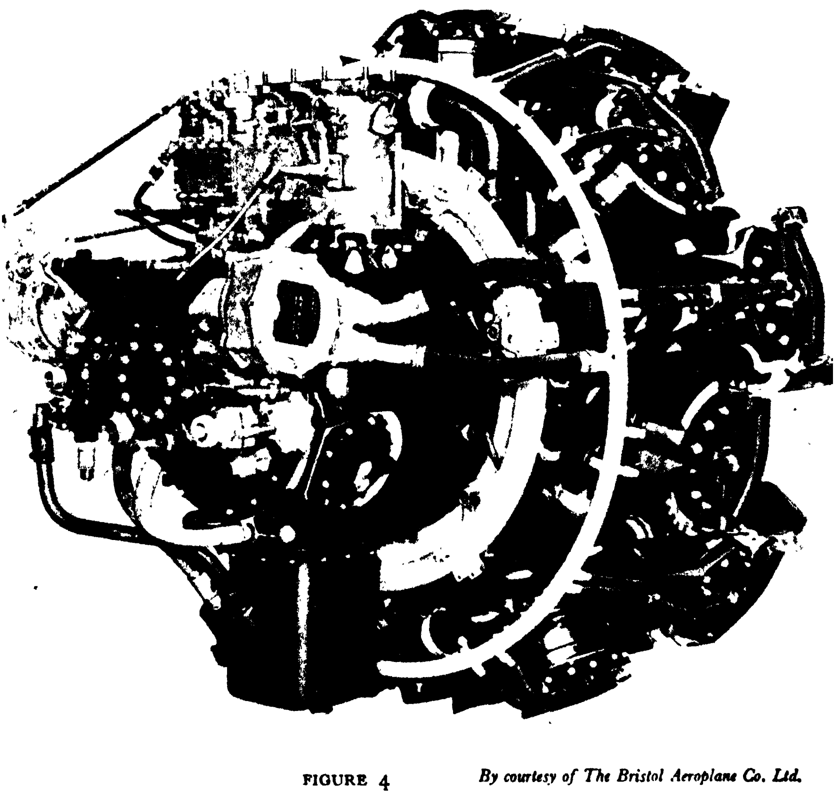
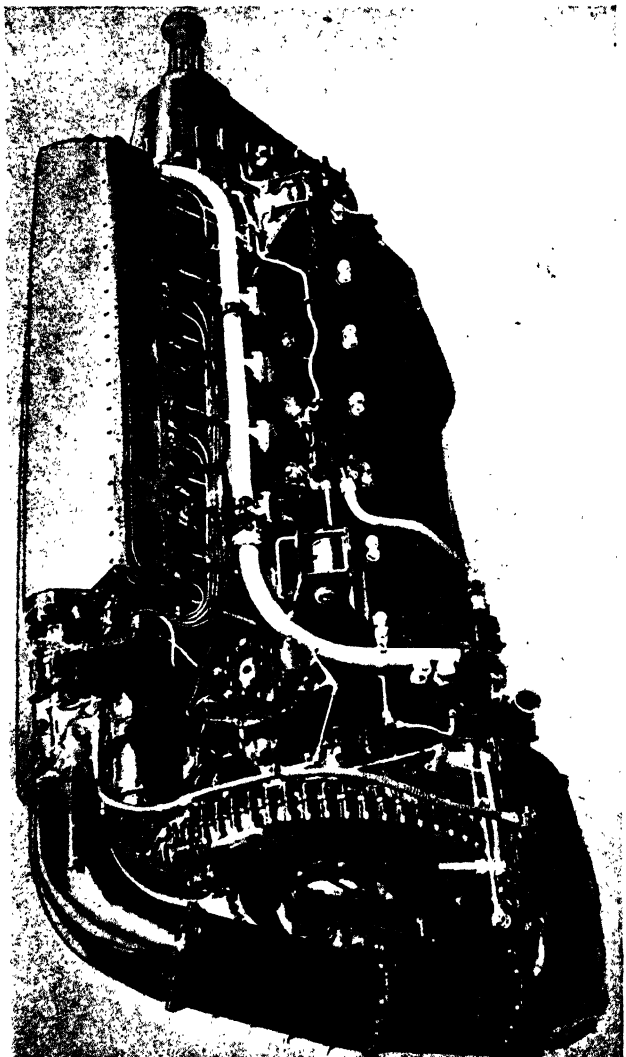


FIGURE 4 *By courtesy of The Bristol Aeroplane Co. Ltd.*

"BRISTOL" HERCULES 100 ENGINE, THREE-QUARTER REAR VIEW



By courtesy of Rolls-Royce Ltd.

FIGURE 5

ROLLS-ROYCE "R" ENGINE, 2,350 B.H.P. FOR 1,630 LB.
(Schneider Trophy Winner, 1931)

RELIABILITY

For future high flying passenger aircraft, provision must also be made for driving cabin pressurisation blowers and the "Bristol" Hercules 120 has an accessory drive capable of transmitting up to 150 h.p. to cover these requirements.

Reliability is obviously an essential requirement of an aero engine, and although the high-power supercharged engine weighs less than 1 lb. per b.h.p., this extraordinary low weight is not achieved at the expense of reliability. In fact, reliability has increased as the weight/power ratio has decreased. Considering the complexity of a modern fully supercharged engine, the reliability is outstanding.

It is interesting to note that when lengthy reliability is sacrificed, as, for example, in the Schneider Trophy racing engines, the weight per horse-power can be much reduced. The Rolls-Royce engine (Fig. 5) fitted to the Supermarine S6 in 1931 had, at full throttle normal r.p.m., the phenomenal output of 2,350 b.h.p. for a weight of 1,630 lb., i.e., approximately 0.69 lb. per b.h.p. (the power was subsequently increased to 2,600 b.h.p.).

Ease of maintenance and overhaul is another factor which has to be taken into account when reliability is considered. Although an aero engine is a "thoroughbred" and as such needs expert attention, it must not require the lengthy preparation and grooming that the thoroughbred requires for so short a trial on the course. It rather must be ready to go "all out" or "all the way" all the time.

Having, therefore, given a brief survey of some of the factors which influence design, the construction of typical aero engines will be considered.

CHAPTER II

Types of Aero Engines

The piston engines in present-day use are of two main types, in-line and radial, the former having its cylinders arranged in line along the length of a crankcase, the latter having cylinders disposed radially from a cylindrical form of crankcase.

IN-LINE TYPE

The in-line engine is made in various forms according to the number of cylinders, and each form has its particular name, but they are all basically of the in-line type.

Up to about 250 b.h.p. a single line of four or six air-cooled cylinders is used, and the engine is invariably of the inverted type, i.e., the cylinders project vertically downwards from the crankcase.

The Cirrus Minor Series I engine illustrated in Fig. 6 is an example of this construction, the maximum power output

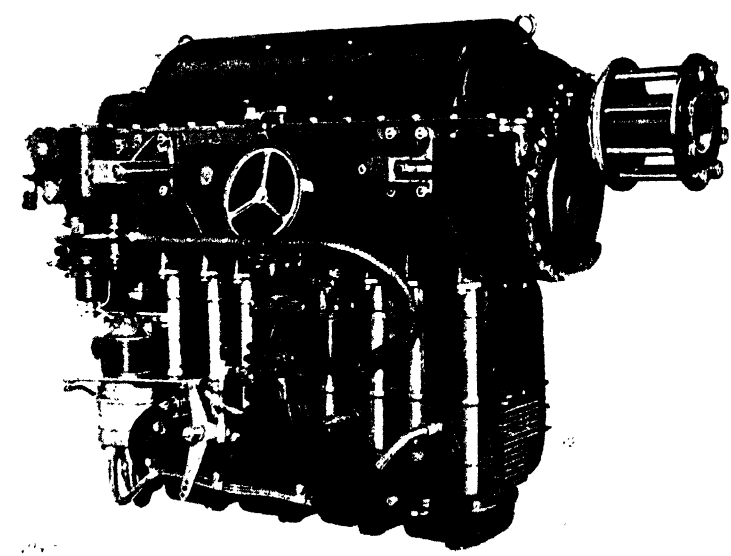


FIGURE 6 *By courtesy of Blackburn Aircraft Ltd.*

90-H.P. CIRRUS MINOR I ENGINE

being 90 b.h.p. The inverted arrangement is favoured because in single-engined aircraft it enables the pilot to have a much improved forward view whilst retaining the propeller thrust line in the same position, and in both single- and multi-engined aircraft the aerodynamic features are improved due to more efficient cowling.

When greater output is required, the cylinders are not increased in size but increased in number, and the six-cylinder in-line type is popular in the 200-300 b.h.p. class.

By adding to the number of cylinders rather than increasing the size, extra power is obtained without an increase in frontal resistance and, due to the extra firing strokes, a smoother-running engine is obtained.

The air cooling necessary for this type of engine is achieved by means of an airscoop and inter-cylinder baffles, so arranged that the air received into the forward open end of the scoop is constrained to move around every cylinder. The small frontal area is an inherent advantage of the in-line type engine, and the Gipsy Queen engine illustrated (Fig. 7) has a take-off power of 295 b.h.p. the capacity being 10.178 litres.

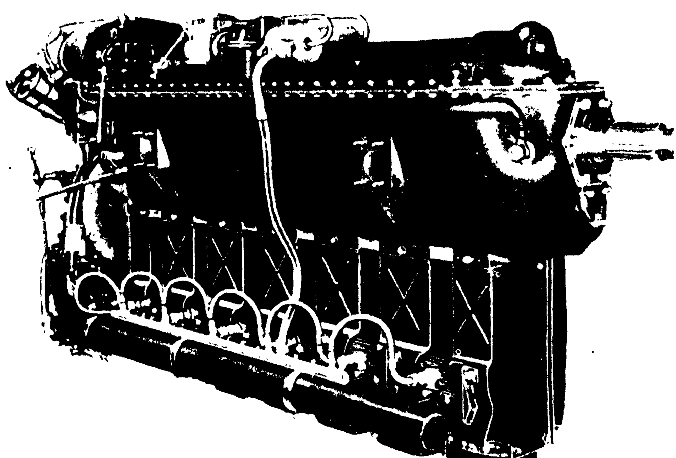


FIGURE 7 *By courtesy of The de Havilland Aircraft Co. Ltd.*

DE HAVILLAND GIPSY QUEEN 51 ENGINE

This type of in-line engine weighs approximately 1.9 lb. per horse-power.

VEE TYPE

When still greater power output is required than can be furnished by a six-cylinder in-line engine, it is not practicable to add further cylinders in the same straight line. The engine would then become very long and unsuitable for efficient installation in an aircraft, and, in addition, the crankshaft would be too long for structural stiffness.

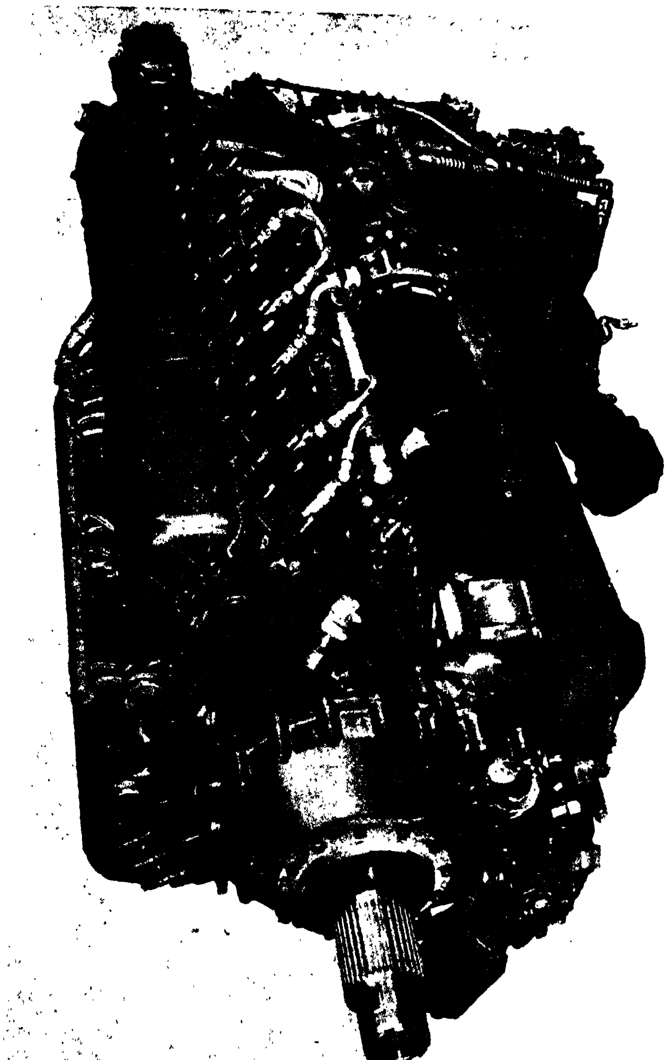
The method adopted is to mount in the form of a Vee two rows of six cylinders on a common crankcase and to couple them to the same crankshaft. The immediate advantage of such a method is that, without increasing the length of either the crankshaft or the crankcase, a very big increase in power is obtained.

Further, only one crankshaft is necessary for what is in effect two engines, and although this has to be more robust than that for a single engine it is very much lighter than two separate crankshafts. The common crankcase has a similar advantage.

The included angle of the Vee is usually 60 deg. in order to obtain a succession of evenly spaced power strokes throughout the two revolutions of the crankshaft during which all cylinders complete one cycle of operations (four-stroke cycle). With twelve cylinders to fire in two crankshaft revolutions the power strokes will therefore occur at 720/12 deg. intervals, i.e., 60 deg.

These power strokes alternate from one cylinder bank to the other, so that if the angle of the V is also 60 deg., the crankshaft, on turning 60 deg., will be in the correct position to receive its power impulse from the next cylinder bank. Typical firing orders for a 12-cylinder V engine are given in Fig. 26, and these, studied in conjunction with the illustration of the crankshaft in Fig. 24, will enable the order to be followed.

Liquid-Cooled Upright Vee Engine.—The liquid-cooled twelve-cylinder 60 deg. Vee poppet-valve Rolls-Royce Merlin and Griffon engines are the best-known examples of this type. The Merlin, of the Battle of Britain days, has undergone



By courtesy of Rolls-Royce Ltd.

FIGURE 8
ROLLS-ROYCE MERLIN T 24-2 ENGINE

continuous development and has been produced in a variety of series with two-speed single-stage and two-speed two-stage superchargers in addition to numerous differences in detail design. With the same capacity of 27 litres the Merlin 130 series has approximately double the power output at the rated altitude of the early war Merlin II (990 b.h.p. at 12,250 ft.).

The Griffon engines of 36.7 litres are basically similar in design. (The Merlin engines are right hand, and the Griffons are left hand tractors. An exception is the Merlin 131 which is a left hand tractor).

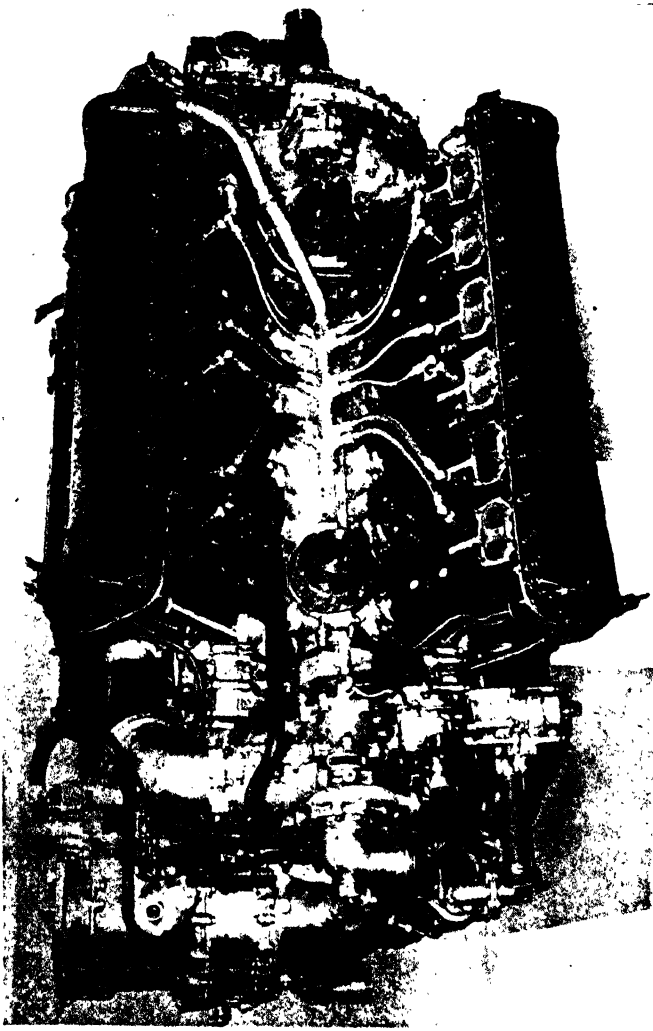
In the early days of liquid-cooled aero engines the cylinders had individual jackets of sheet steel welded to flanges formed on the cylinder itself but in modern types the cylinders for each bank are all contained in one long casing, the complete unit being termed a monoblock. This monoblock type construction is now the normal method for liquid-cooled engines, as it forms a more compact unit than could be achieved by other forms of construction.

The actual steel cylinders are inserted into an aluminium alloy casting which forms the foundation of the monoblock, and passages provided in the casting and between each cylinder liner allow circulation of the coolant by a pump.

Another feature of this type of engine is the method of valve operation by means of an overhead camshaft which is located along the length of the top of each block, the valve operating mechanism being totally enclosed by a cover which is secured to the top of the block.

The liquid-cooled supercharged Vee engine is capable of very high power outputs and has the inherent low frontal area of its type. For example, the Griffon 65 engine, with two-speed two-stage supercharger has a maximum output of 2,035 b.h.p. for a capacity of 36.7 litres and there is no doubt that development will increase the output. On the performance given the power is equivalent to 281 b.h.p. per sq. ft. of frontal area.

Although the Merlin and Griffon are upright Vee engines, there are other Continental liquid-cooled engines of the inverted Vee type.



By courtesy of Rolls-Royce Ltd.

FIGURE 9

ROLLS-ROYCE 24-CYLINDER VULTURE ENGINE

When more powerful engines are required, the cylinder blocks are arranged in an X or Cruciform fashion, so that there is in effect an upright and an inverted Vee mounted on the same crankcase and driving a common crankshaft. At the time of writing there are few particulars available of current engines of this type, but an illustration of the Rolls-Royce Vulture 90 deg. X engine is given in Fig. 9. This engine was in the process of development but was discontinued in the early part of the war. At that time it had a two-speed supercharger giving 1,845 b.h.p. at 3,000 r.p.m. at 5,000 ft. in low gear and 1,710 b.h.p. at 15,000 ft. in high gear for a cubic capacity of 2,592 cu. in. If higher capacity and more powerful piston engines are developed there will very likely be a return to this type of multi-bank as the existing cylinder sizes of the present Vee twelve are considered optimum. It is interesting to note that one of the latest German designs—the Junkers Jumo 222a, had a radial arrangement of six four-cylinder blocks, with epicyclic reduction gearing and two-speed supercharger. Maximum power was 2,500 b.h.p. for a weight of 2,400 lb.

H TYPE

In this engine advantage is taken of the low frontal area of the in-line type and the high operational speeds and powers obtainable through a large number of small cylinders.

As it is not practical with this arrangement to couple four connecting rods to the same crank, the opposing units are coupled to a common crankshaft, the two crankshafts being geared to the same central propeller shaft.

The new Rolls-Royce Eagle engine (Fig. 10), a 24-cylinder, liquid-cooled, sleeve-valve, flat H, represents a new phase in the development of the piston engine by the makers of the world-famous Merlin and Griffon Vee types. With cylinders 5.4 in. × 5.125 in. bore and stroke, a total swept volume of 46 litres and a maximum power output of 3,500 b.h.p. at 2,750 ft., for 3,900 lb., it is the most powerful piston engine in production. Among other notable design features is a two-

speed two-stage supercharger and gearing for contra-rotating propellers.

The Napier Sabre 24 cylinder, sleeve-valve, liquid-cooled engine (Figs. 11 and 12), represents another technical achieve-

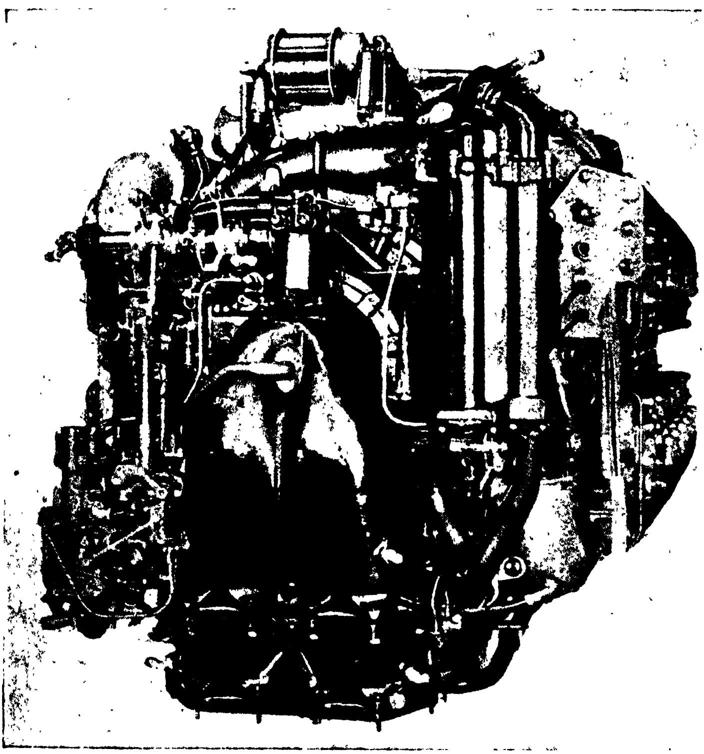


FIGURE 12 *By courtesy of D. Napier & Son Ltd.*

NAPIER SABRE VII — REAR VIEW

ment in multi-cylinder piston engines. In contrast to the vertical arrangement of the air-cooled Dagger, the cylinder blocks of the Sabre are horizontally opposed so that the twin crankshafts are housed one above the other in the vertically divided crankcase. The upper and lower cylinder banks of each side are formed in a common light alloy casting, each cylinder having a separate head, die cast in aluminium alloy. The

engine can in fact be considered as two horizontally-opposed twelve-cylinder units mounted one above the other and geared to a common propeller shaft. A great advantage of this layout is that all sparking plugs, cylinder heads, etc., are very accessible for maintenance, and the exhaust stubs—common to each vertical pair of cylinders—are well disposed on the centre line of the engine for ejecting on each side of the cowling. The auxiliaries are mostly mounted either above or below the cylinder blocks and are thus also very accessible for inspection.

The compactness of the complete engine is evidenced by the illustration yet it is difficult to realize that in the overall dimensions of length 6 ft. 11 ins., width 3 ft. 4 ins., height 3 ft. 11½ ins., is contained a unit giving 3,000 b.h.p. (with water-methanol injection) for take-off (Series VII), and it is certain that development will increase this performance. The short stroke of 4¾ ins., permitting a high rotational engine speed (3,850 r.p.m. max.), enables an exceptionally large output per unit capacity to be produced. The 3,000 b.h.p. for 36.7 litres is equivalent to 81.7 b.h.p. per litre for a weight/power ratio of only 0.84.

RADIAL TYPE ENGINES

With its cylinders disposed radially around a circular form of crankcase this engine (Fig. 13) is the most common air-cooled type for medium and high powers.

It is of course a logical arrangement to dispose each cylinder so that it faces the cooling air stream, but there is also another important reason. The crankshaft of an engine is by far the heaviest single component, and any arrangement of cylinders whereby its length can be reduced will be very effective in reducing this weight.

In the radial engine as many as nine connecting rods can operate on a single crankpin, so that the length and weight of the shaft and of its crankcase are reduced to a minimum. This feature enables a low weight/power ratio to be obtained

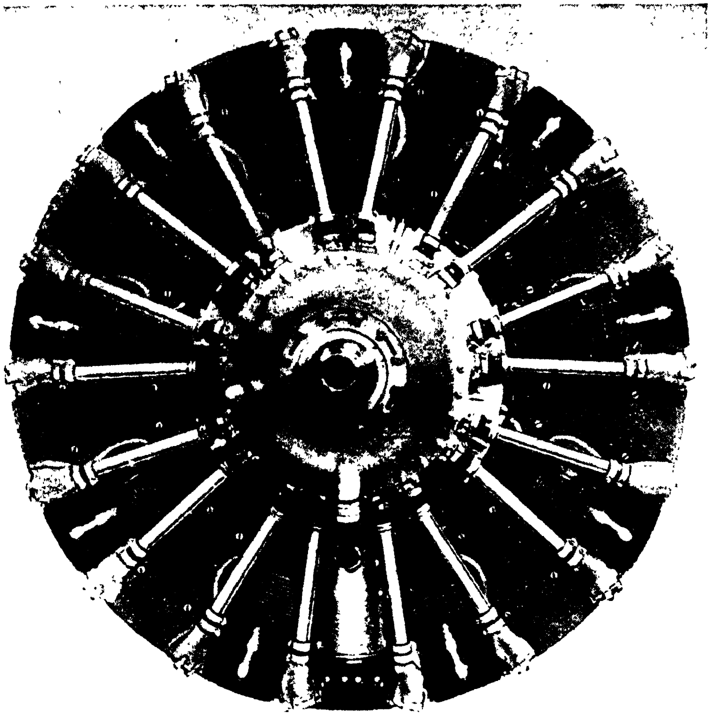


FIGURE 13 *By courtesy of Armstrong Siddeley Motors Ltd.*

ARMSTRONG SIDDELEY 9-CYLINDER 850-B.H.P. COUGAR ENGINE

and the short crankshaft is free from the " flexing " experienced with long shafts having numerous throws.

The question may be raised of the large frontal area producing excessive drag, thereby detracting from this efficient cylinder arrangement, but modern methods of scientific cooling and efficient cowling have greatly reduced the drag, as is evident by the high performance of such typical radial-engined aircraft as the " Bristol " Brigand and Hawker Sea Fury with " Bristol " Centaurus engines.

The " Bristol " and Armstrong Siddeley engines are the best known radial types in this country, the former being of high power output, the latter covering a range from low to

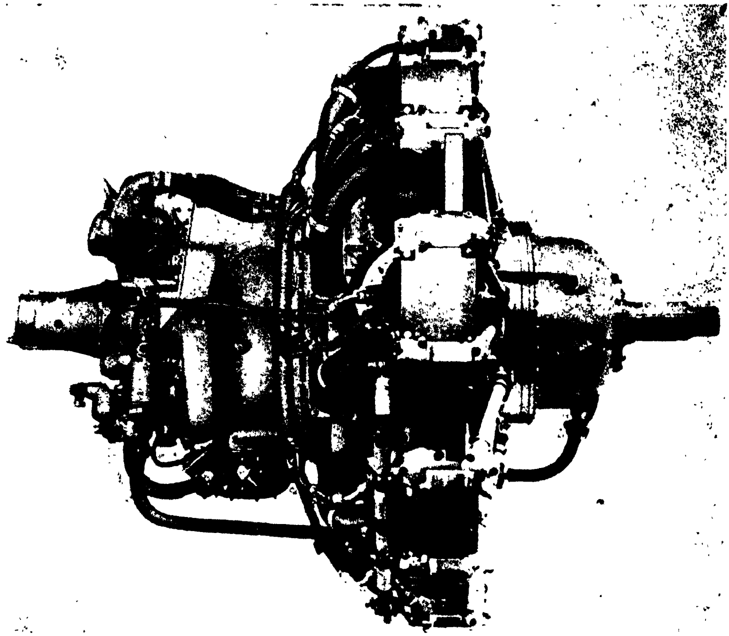


FIGURE 14 *By courtesy of Armstrong Siddeley Motors Ltd.*

ARMSTRONG SIDDELEY COUGAR ENGINE—SIDE VIEW

medium powers. The constructional differences of these engines will be subsequently described.

The engine illustrated in Figs. 13-14 is an example of a medium-power, supercharged and geared single-row radial engine of the ordinary poppet-valve type. The reduction gearing is so arranged that the axis of the propeller shaft is in line with that of the crankshaft, and thus there is no interference with the airflow over the cylinders.

The radial form of construction has a great advantage from the maintenance point of view if a cylinder removal is necessary, as it is much more simple to remove an individual cylinder. On Armstrong Siddeley engines there are two valves per cylinder, one inlet and one exhaust, operated by rocker, push-rod and tappet, the inlet and the exhaust port both facing rearwards.

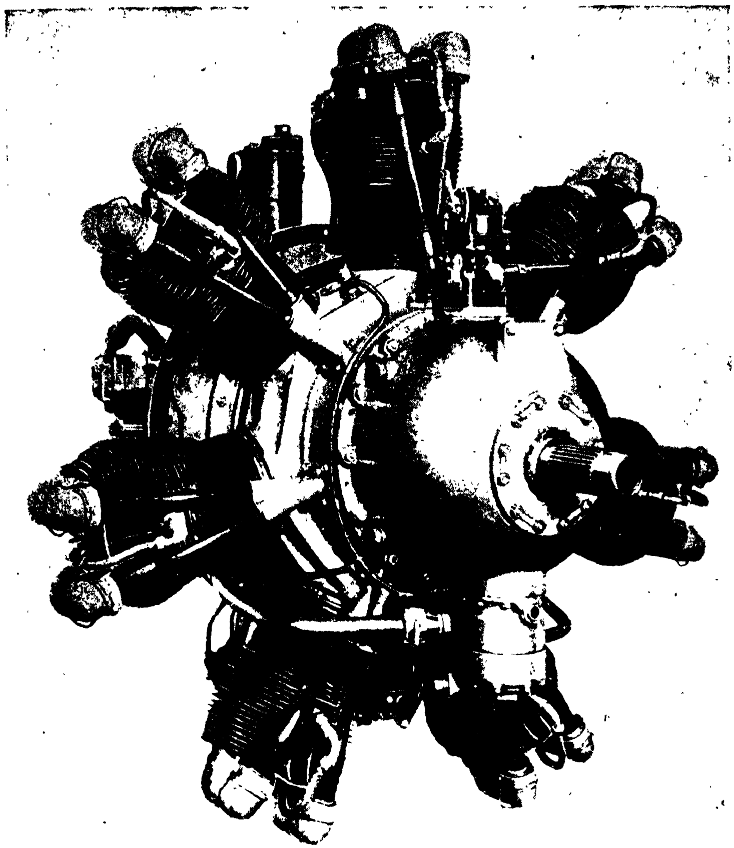
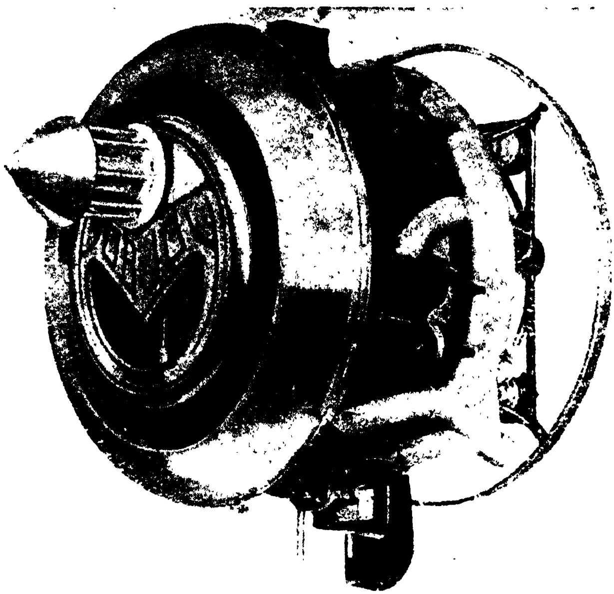


FIGURE 15 *By courtesy of Armstrong Siddeley Motors Ltd.*

ARMSTRONG SIDDELEY 7-CYLINDER CHEETAH XV ENGINE

On account of its circular type of crankcase the radial engine is very well adapted for the centrifugal type supercharger used on British engines. The supercharger casing, being also of circular form, can be fitted to the rear of the crankcase, where it blends in with the general outline with little increase in overall length. Another advantage is that a uniform distribution of the petrol-air mixture is possible, as each cylinder is at the same radius from the supercharger delivery.



By courtesy of Pobjoy Airmotors & Aircraft Ltd.

FIGURE 16

POBJOY NIAGARA III ENGINE

One of the most interesting low-powered geared radial engines was the Pobjoy Niagara illustrated in Fig. 16. This compact seven-cylinder power unit of only 26.5 in. overall diameter had a maximum power output of 95 b.h.p. at 3,650 r.p.m. for a nett dry weight of 156 lb.

With the very small size of cylinder used (77 mm. bore, 87 mm. stroke) there could be only two valves per cylinder, and these were operated by rockers actuated by push rods at the back of the cylinders.

Two-row radial engines are also manufactured, and in the poppet-valve type the Wright Cyclone 18-cylinder engine, manufactured by the Wright Aeronautical Corporation of America, is one of the most powerful developed. Many unique features are incorporated in the range of Cyclone engines, one of the most interesting being the adoption of a forged steel crankcase. Other features of the engine are illustrated subsequently.

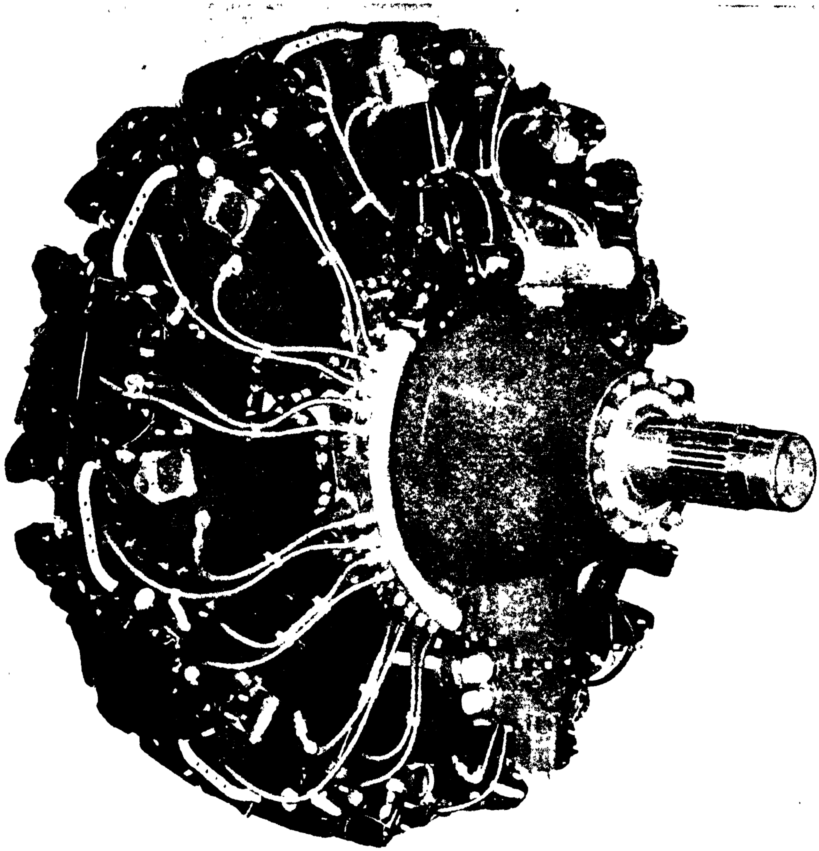


FIGURE 17 *By courtesy of Wright Aeronautical Corporatio*

WRIGHT AERONAUTICAL CORPORATION CYCLONE 18-CYLINDER DOUBLE-ROW ENGINE

As seen from Fig. 17, the two rows of cylinders are staggered in relation to each other in order that the rear row may be efficiently cooled.

It will be noted that, unlike the earlier Bristol Pegasus and Mercury engines whose push rods for inlet and exhaust valve operation were located one behind the other on the centre line of the cylinder, the Cougar, Cheetah and Cyclone engines have their push rods "splayed" and that

only one inlet and one exhaust valve per cylinder is operated, both ports facing rearwards in the case of the Cougar and Cheetah. The Wright Cyclone series have the exhaust ports facing the front.

The new Pratt and Whitney Wasp Major engine (Figs. 18 and 19), is an excellent example of the development of multi-bank radial engines in the quest for still higher power output without increase in engine diameter or cylinder dimensions. Twenty-eight cylinders are disposed in four banks of seven, each row being staggered in relation to the other in a helical arrangement so that each cylinder projects into the air stream. The frontal area is no greater than that of the 18-cylinder Double Wasp, while the diameter is only one inch greater than that of the original Wasp which developed 410 b.h.p. in 1925.

Although the basic elements of design closely follow those used in service-proved engines, several innovations and improvements have been made, notably: deep finned, forged aluminium alloy cylinder heads ; duralumin cylinder muffs of special design for use interchangeably with tractor or pusher installation ; the elimination of the conventional ignition harness through the use of seven interchangeable magne ., one for each bank of cylinders ; a vibration free crankshaft and improved vibration dampers to inhibit vibration from power impulses and reciprocating masses ; an automatically controlled, hydraulically driven variable speed supercharger ; and the radial mounting of accessories about the periphery of the accessory drive case, instead of on the rear of the engine, to provide excellent maintenance accessibility.

For a piston displacement of 4,360 cu. ins. (71.45 litres) and dry weight of 3,405 lb. the Wasp Major develops over 3,650 b.h.p.

THE SLEEVE-VALVE ENGINE

The poppet valves of the normal engine impose a limit on the operating efficiencies and power output of an internal combustion engine. The valves restrict the gas flow and the hot exhaust valve limits the compression ratio or degree of supercharge.

There is also a limit to power output per cylinder owing to the limitation of the metal of which the valves are made. The cooling of the exhaust valve presents great difficulty, and even with sodium-filled valves the operating temperature is in the neighbourhood of 600 deg. C., so that it is difficult to ensure a continuous gas-tight seal between the valve and its seating.

Apart from the limitations imposed by the valve itself, the valve-operating mechanism presents difficulties at high speeds of operation due to the tendency for the tappet to leave its cam.

In order to overcome the difficulties attendant upon the use of poppet valves, the sleeve-valve engine was designed. After many years of research and development the Bristol Aeroplane Co., Ltd., produced the first satisfactory sleeve-valve aero engine in the world, and it is due to this that powerful engines of this type with all its advantages are to-day operating on many British aircraft.

Instead of governing the gas inlet and exhaust by means of the ordinary valve, a sleeve valve (Fig. 49), in which ports are cut, has a combined reciprocating and partly rotational movement in the cylinder. The ports in the sleeve traverse similar ports cut in the wall of the cylinder barrel, and thus the inlet and the exhaust gases are able to enter and to leave the interior at the correct periods in the cycle of operations.

ADVANTAGES OF SLEEVE-VALVE OPERATION

The advantages of sleeve-valve operation are numerous, and the main ones are listed below.

1. There are large port areas unrestricted by valves, thus providing better induction and scavenging.

2. The sleeve-valve timing is not affected by the speed of operation, as it is positively driven from the engine.

3. Cooler operating conditions in the cylinder due to absence of heated valves enables higher compression ratios or degrees of supercharge to be used, thereby providing better fuel economy and power output.

4. Elimination of cams, tappets, push rods and rocker mechanism. This is a considerable advantage from the

maintenance point of view, as there are no valve clearances to be checked or re-set as with the poppet valve operating gear ; neither is there the multiplicity of small parts.

5. Exceptionally "clean" engine.

"Bristol" double-row sleeve-valve air-cooled engines are at present the only radial types in active production, and Figs. 20-21 illustrates the 18-cylinder Centaurus from which

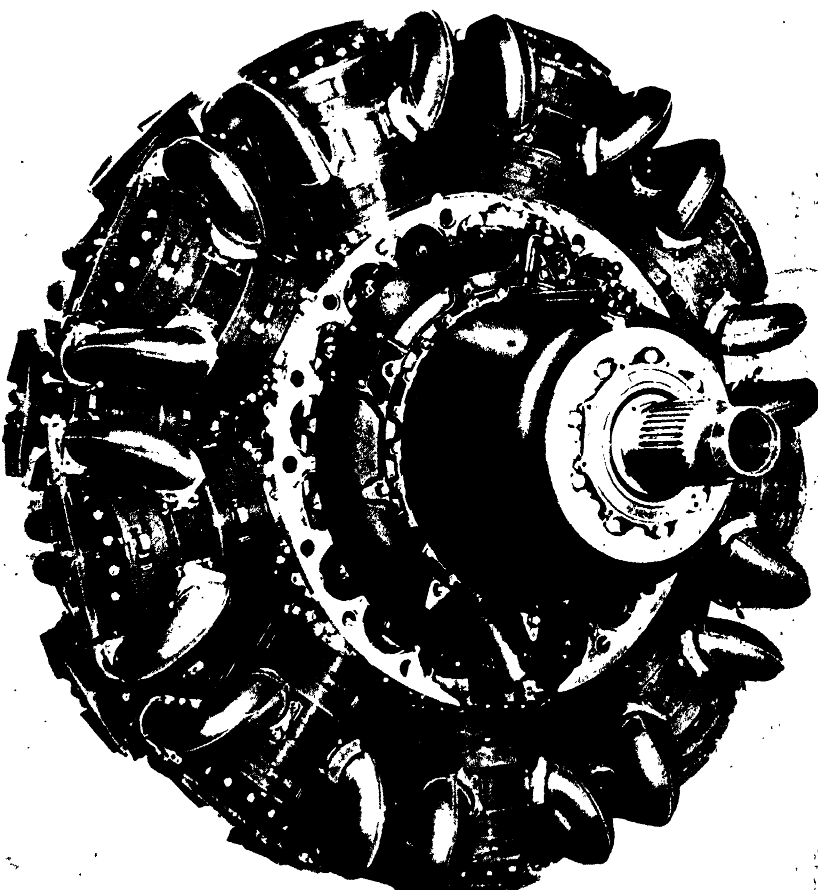


FIGURE 20 *By courtesy of The Bristol Aeroplane Co. Ltd.*

"BRISTOL' CENTAURUS 18-CYLINDER SLEEVE-VALVE ENGINE

the characteristic appearance of these engines may be judged. The exhaust ports face forwards as with other "Bristol" engines, but in the aircraft installation the exhaust pipes are swept rearwards, as indicated in Fig. 3, unlike the Pegasus and Mercury poppet-valve engines which had an exhaust collector ring at the nose.

The 14-cylinder Hercules and 18-cylinder Centaurus engines of 38.7 and 53.6 litres respectively embody the many years experience in test and operation of "Bristol" sleeve-valve types and are now being developed for power outputs of 2,500 b.h.p. and 3,500 b.h.p. The Hercules HE.20 SM is a forward development of the 100 series and is the prototype of the Hercules 200 and 230 engines. The HE 20 SM having a single-stage two-speed supercharger with a Hobson-R.A.E. fuel injector equipped for methanol-water injection has already been tested at 2,500 b.h.p. for take-off for a weight of approximately 2,000 lb. The production engines of this type will embody reduction gears suitable for reversing propellers.

The Centaurus CE. 22 SM is likewise a development of the XVIII and 57 series, and is the prototype of the 130 engine which will power civil transport aircraft. Testing of this engine has been carried out at powers substantially in excess of 3,000 b.h.p., the immediate development being up to 3,500 b.h.p. This engine weighs approximately 2,900 lb.

A single-stage two-speed supercharger is fitted with twin lateral air intakes carrying the fuel spray nozzles fed by a Hobson-R.A.E. injector. The double-entry air intakes can be seen in Fig. 21. Reduction gearing is suitable for reversing propellers and an alternative gear for counter-rotation can be provided.

The latest engines although of the same basic design as the earlier types are much altered in detail, particularly in respect of the supercharger. This with the Hobson-R.A.E. injector now fitted in place of the float carburettor previously employed, has resulted in considerable improvement in altitude performance and fuel economy.

Both engines have aluminium-alloy cylinder barrels and heads, forged aluminium alloy pistons and alloy-steel sleeve

FIGURE 21 *By courtesy of The Bristol Aeroplane Co. Ltd.*

"BRISTOL" CENTAURUS ENGINE — THREE-QUARTER REAR VIEW

valves. The built-up three-piece crankshaft is housed in a three-piece crankcase of forged aluminium alloy. These and other constructional features are illustrated subsequently. The small cowls over each cylinder head are for the purpose of directing an air current into and so cooling a pocket which is formed in the head.

CHAPTER III

Constructional Features of Typical Aero Engines

Having briefly described the main types of aero engines, it will be of interest to examine their general construction, and in order to view the internal details it will be imagined that the engines have been dismantled.

THE CRANKSHAFT

Four-throw Crankshaft.—The four-cylinder in-line engine has a crankshaft of the type illustrated in Fig. 23, from which it will be noted that there are four cranks or "throws," upon the crankpins of which operate the big ends of the connecting rods (Fig. 35).

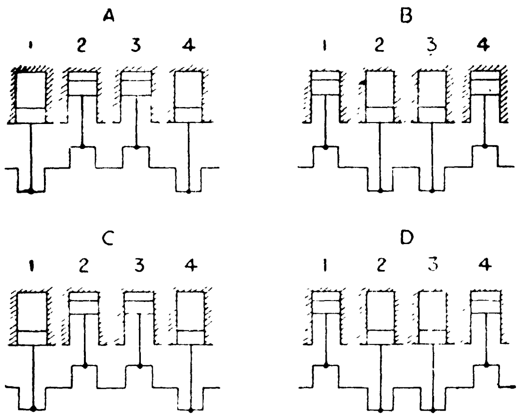
The throws are arranged in pairs set at 180 deg. to each other in order that the sequence of power strokes may be evenly distributed over the two revolutions in which all cylinders of a four-stroke engine must fire. For example, for even power impulses one cylinder must fire each 720 deg./4=180 deg. revolution of the crankshaft, and the diagrammatic illustration of Fig. 22 shows the full sequence of operations.

The six journals of this shaft are supported in bearings in the engine crankcase (Fig. 60), these bearings being lined with anti-friction metal.

The journals and crankpins are not solid but are bored out, as the mass of metal around the axis of the shaft adds nothing to its strength, while the bore provides a passage through which oil can be fed to the working surfaces. To provide an oil-tight compartment the bores are fitted with sealing caps, and the oil is led from one bore to another by means of a hole drilled through the length of the crankweb.

At the forward end of the front journal a ball-bearing thrust race is fitted, and this forms the means by which the pull of the propeller is transferred with minimum friction from the

shaft to the crankcase and thence to the engine mounting in the airframe. A thrust race is fitted to all types of aero engine crankshafts or to the propeller shaft according to whether the engine has a direct drive or reduction gear.



SEQUENCE	CYLINDER NUMBER 1	2	3	4	C/SHAFT REVS
A	POWER	EXHAUST	COMPRESSION	INDUCTION	½
B	EXHAUST	INDUCTION	POWER	COMPRESSION	1
C	INDUCTION	COMPRESSION	EXHAUST	POWER	1½
D	COMPRESSION	POWER	INDUCTION	EXHAUST	2

FIRING ORDER 1. 3. 4. 2.

FIGURE 22

SEQUENCE OF OPERATIONS, 4-CYL. ENGINE

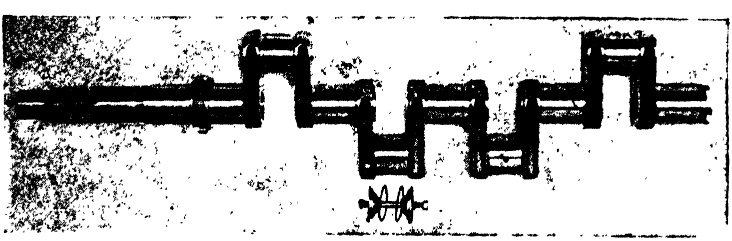


FIGURE 23 *By courtesy of The de Havilland Aircraft Co. Ltd*

GIPSY MAJOR 31, FOUR-THROW CRANKSHAFT

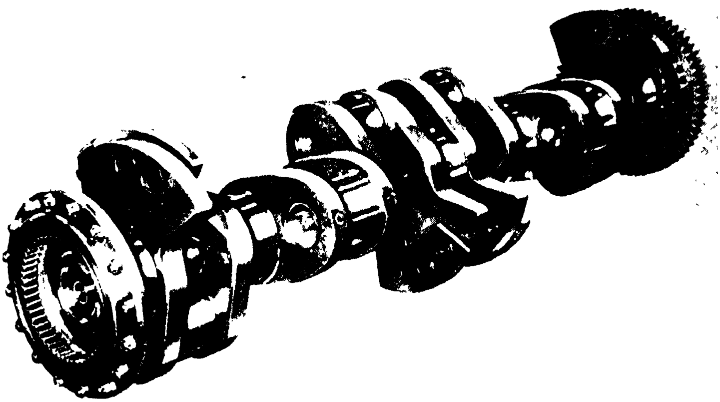


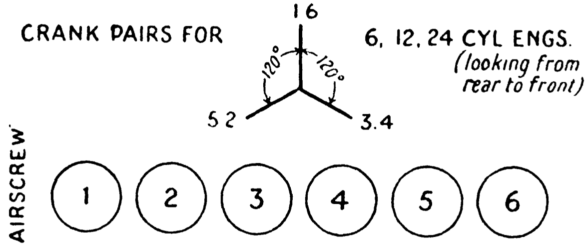
FIGURE 24 *By courtesy of Rolls-Royce Ltd.*
SIX-THROW CRANKSHAFT, ROLLS-ROYCE GRIFFON 65 ENGINE

Six-throw Crankshaft (Fig. 24).—For six cylinders in line or for a Vee-twelve engine a six-throw crankshaft is used, the throws being in three pairs, each pair being set at 120 deg. to the other (i.e., 720/6). The same shaft is used for the Vee-twelve engine, as this engine is really two six-cylinder in-line units coupled together, two connecting rods—one from each unit—working on the same crankpin.

The same arrangement is also used for the vertically opposed six-cylinder units of the H type or the opposing units of X engines.

It will be noted that some of the crankwebs are extended, and this is done in order that the shaft may be in better dynamic balance. Typical firing orders for six-cylinder, twelve-cylinder Vee, and 24-cylinder 90 deg. X engines are given in Figs. 25, 26 and 27.

The Napier Sabre with its twenty-four horizontally opposed cylinders and twin crankshafts has a more unorthodox firing order. The crankshafts which rotate in the same direction are also in phase as indicated in Fig. 28 so that two cylinders fire simultaneously.

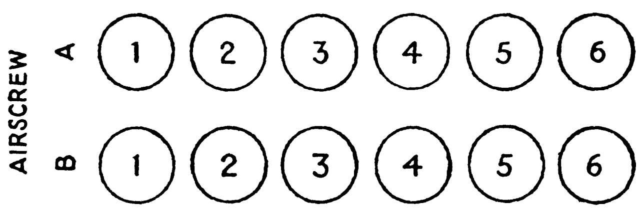


CRANKSHAFT ROTATION	ALTERNATIVE FIRING ORDERS (CYL. NOS)					
R.H.*	1	5	3	6	2	4
L.H.*	1	4	2	6	3	5

*The direction of rotation will be reversed if crankthrows 3, 4 and 2, 5 are interchanged.

FIGURE 25

TYPICAL FIRING ORDERS FOR 6-CYL. IN-LINE ENGINE



FIRING ORDER FOR L.H. ROTATION (C/SHAFT)

A 1 4 2 6 3 5

B 6 3 5 1 4 2

FIRING ORDER FOR R.H. ROTATION (C/SHAFT)

A 6 2 4 1 5 3

B 1 5 3 6 2 4

FIGURE 26

FIRING ORDERS FOR 60-DEG. V-TWELVE ENGINE

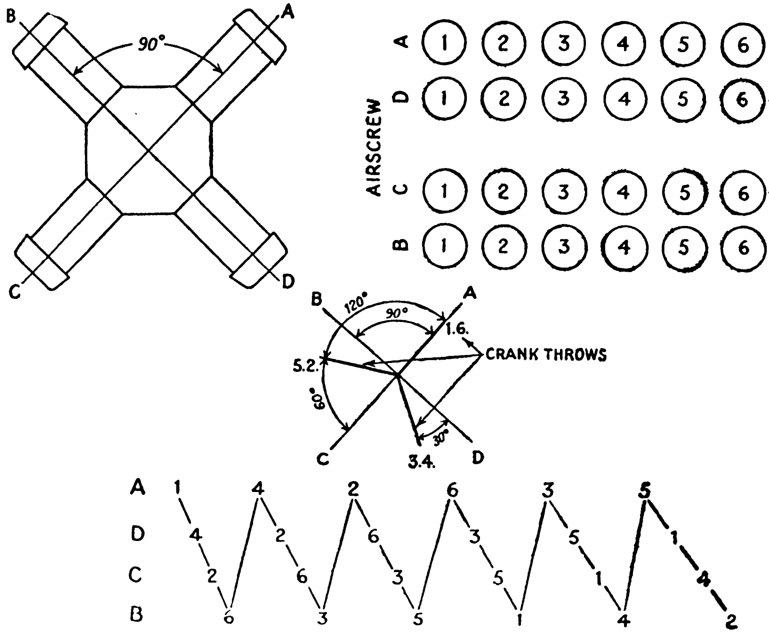


FIGURE 27
FIRING ORDER FOR 90-DEG. 24-CYLINDER ENGINE

The order of firing and pairs of cylinders can be traced readily from the arrangement given in the diagram. On the engine, both upper and lower cylinders banks on the port side are numbered 1 to 6 from the rear while those on the starboard are numbered 7 to 12 from front to rear. In the diagram the throws of each shaft are numbered 1 to 6 and the pairs at 120 deg. are numbered according to their firing order so that for the starboard cylinders, these crank numbers must be translated into cylinder numbers. For convenience the starboard cylinders have their respective crank numbers placed over them in Fig. 28.

Thus, cylinders 1 top and 6 bottom of the port side fire together. The crankshafts turn 60 deg. and crank 4 of the top crankshaft and 3 of the bottom are in position for firing by the starboard cylinders. No. 4 crank is operating No. 9 cylinder

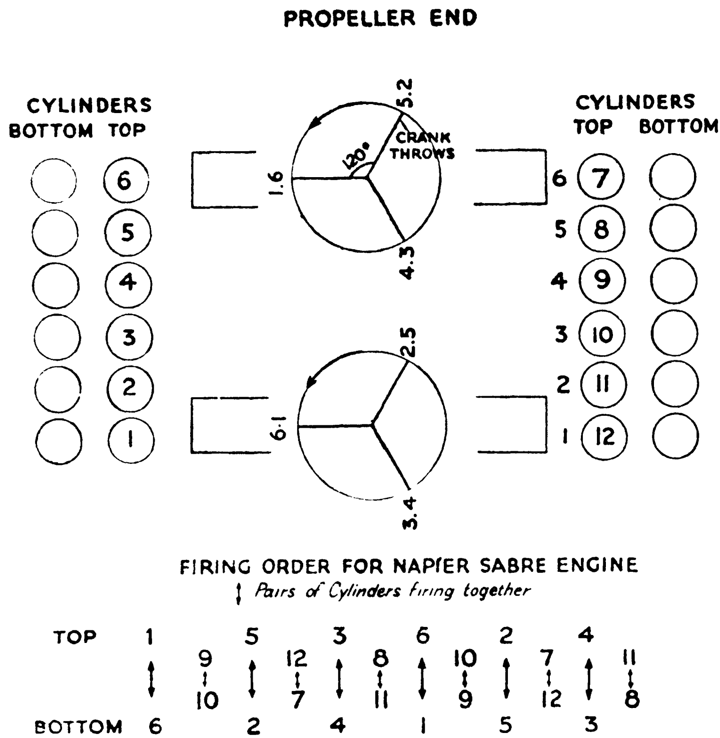


FIGURE 28

FIRING ORDER FOR NAPIER SABRE ENGINE

and No. 3 crank will be operating No. 10 cylinder so that Nos. 9 top and 10 bottom are the next to fire together.

The complete firing order given in Fig. 28 is displaced so that the fundamental order 1, 5, 3, 6, 2, 4 can be easily identified. In this instance the order gives a left hand rotation as cranks 2 and 5 are to the right of 1 and 6 when viewing the shaft from rear to front with 1 and 6 vertical. As a point of interest the Rolls-Royce Griffon has this arrangement while the Merlin has 2 and 5 cranks to the left as shown in Fig. 36. For the same firing order the crankshafts of these two engines will therefore rotate in opposite directions.

Radial Engine Crankshaft.—This shaft has the same number of crank throws that there are rows of cylinders, as the connecting rods of each row operate on the same crankpin. As radial engines are at present of single or double-row type, there will be either one or two throws according to the particular engine. (Refer to Fig. 19 for multi-throw shaft).

There are, however, two types of crankshaft, that in which the shaft is made in one piece, and that which is built up of two or more parts, the latter type being often referred to as a coupled shaft.

The "Bristol" crankshaft illustrated in Fig. 29 is of the coupled type, the rear crankweb being split and bored for the purpose of mounting upon the crankpin, on which it is gripped by a stout bolt.

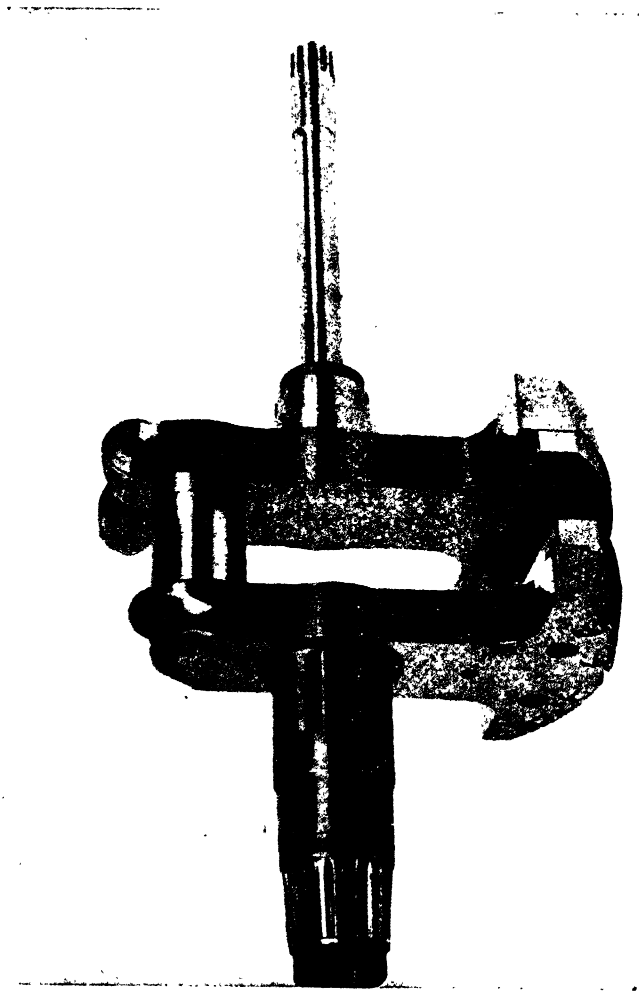
This method of construction is to enable a special type of connecting rod to be used in which the big end is not split for assembly, so that the rod has to be slid onto the crankpin. It is therefore necessary to have a detachable crankweb.

It will be noted that the shaft is of robust construction compared with a single-throw of the in-line cylinder type, this being necessary as up to nine connecting rods operate on the one crankpin.

The massive counterweights are necessary to balance the weight of the combined connecting rods so that the rotating crankshaft will not be subjected to out-of-balance forces.

Another construction is employed for the two-throw crankshaft illustrated in Fig. 30 of the "Bristol" Hercules double-row sleeve-valve engines. In this case the front detachable portion, from which the heavy drive to the reduction gearing and to the propeller is taken, is secured by two stout bolts, the crankweb being split by an angular ; cut (the crankshaft for the Centaurus engine has two bolts securing each maneton joint).

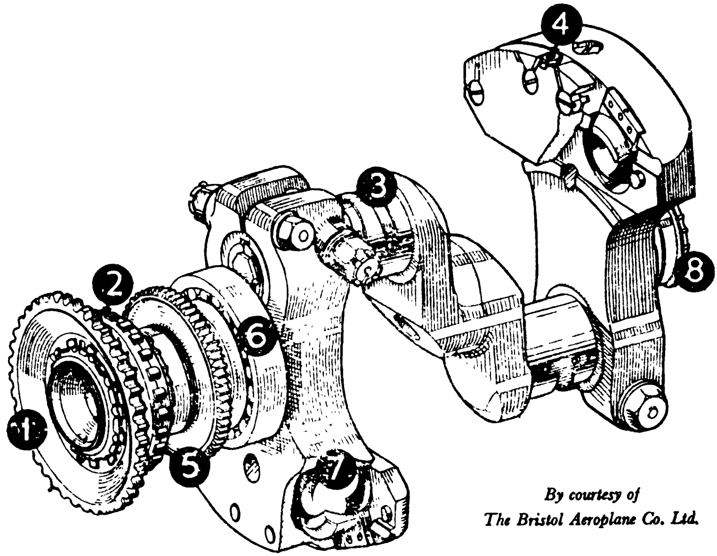
In this shaft the auxiliary balance weights fitted to the front and rear crankwebs incorporate spherical vibration dampers (Salomon damper balls), to absorb torsional and flexural vibrations. An oil sprayer jet is also fitted to each balance weight.



By courtesy o The Bristol Aeroplane Co. Ltd.

FIGURE 29
"BRISTOL" PEGASUS ENGINE, SINGLE-THROW,
COUPLED CRANKSHAFT

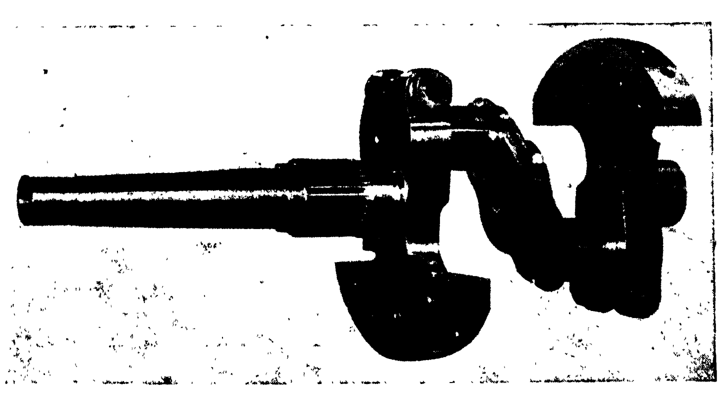
1. Reduction Gear Driving Wheel.
2. Front Cover Bearing.
3. Fixed Big-end Bush.
4. Oil Jet.
5. Crankshaft Gear.
6. Front Main Bearing.
7. Salomon Damper Balls.
8. Rear Main Race.



By courtesy of
The Bristol Aeroplane Co. Ltd.

FIGURE 30

"BRISTOL" TWO-THROW COUPLED CRANKSHAFT (HERCULES ENGINE)



By courtesy of Wright Aeronautical Corporation

FIGURE 31

TWO-THROW CRANKSHAFT OF WRIGHT CYCLONE 18-CYLINDER ENGINE

On the later Hercules and the Centaurus crankshafts white metalled steel bearing sleeves are shrunk on to the crankpins to form the big end bearing.

The Wright Cyclone 18 crankshaft (Fig. 31) is built-up in three sections also to permit the use of single-piece master rods. On this shaft a tapped hole is provided for the crankpin clamping bolt. A special feature is the Wright Dynamic Damper mounted on both crankwebs by means of stainless steel suspension pins. The free moving counterweight permits oscillations corresponding to the power impulses and by applying counter-torque to each of the torque fluctuations, damps out the torsional vibrations of the shaft.

When a split type big end connecting rod is employed, the

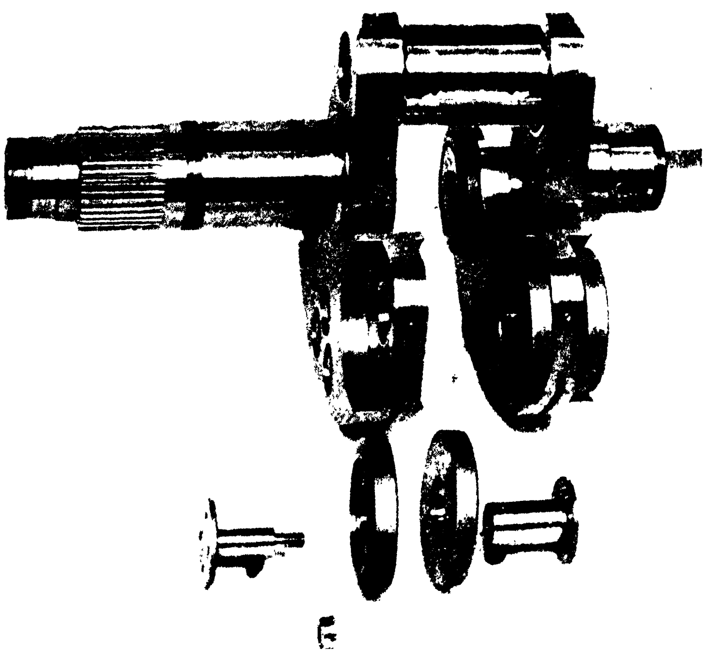


FIGURE 32 *By courtesy of Armstrong Siddeley Motors Ltd.*

ONE-PIECE CRANKSHAFT (ARMSTRONG SIDDELEY CHEETAH XV ENGINE)

crankshaft is made in one piece, as it is possible to assemble the rod to the crankpin. The Armstrong Siddeley Cheetah range of engines are fitted with this type of shaft, one of which for the Cheetah XV is shown in Fig. 32. This shaft has pendulum type vibration dampers fitted to each crankweb as shown.

Firing Order.—In order to obtain as even a turning effort as possible, radial engines have power strokes in alternate cylinders throughout the two crankshaft revolutions which are necessary to complete the four-stroke cycle. The practice is for the odd numbers to fire in the first revolution and the even numbers in the second. For a seven-cylinder engine the firing order would therefore be 1, 3, 5, 7, 2, 4, 6.

For a double-row radial engine the power strokes alternate from one row to the other, each row maintaining the sequence as given above for the single-row engine. The double-row engine having the throws of its crankshaft set at 180 deg. will therefore have a firing order of the following general type (see Fig. 33) : 1F, 2R, 3F, 4R, 5F, 6R, 7F, 1R, 2F, 3R, 4F, 5R, 6F, 7R.

In the case of the " Bristol " double-row Hercules engines, No. 1 cylinder is the vertical cylinder in the rear row, and the cylinders are numbered consecutively clockwise from the front, so that the firing order is 1, 10, 5, 14, 9, 4, 13, 8, 3, 12, 7, 2, 11, 6 (Fig. 34).

If the cylinders on each bank are numbered 1 to 7 consecutively, it will be noted that the firing order remains 1, 3, 5, 7, 2, 4, 6.

CONNECTING RODS

In-line Engines.—The type of rod fitted to the four- and six-cylinder in-line engine is illustrated in Fig. 35. The big end is split for the purpose of assembling the rod to its crankpin and encloses a split bearing.

This type of bearing usually consists of a split steel shell which is lined on its inside surfaces with white-metal, a tin base alloy, or lead-bronze, a copper-lead alloy.

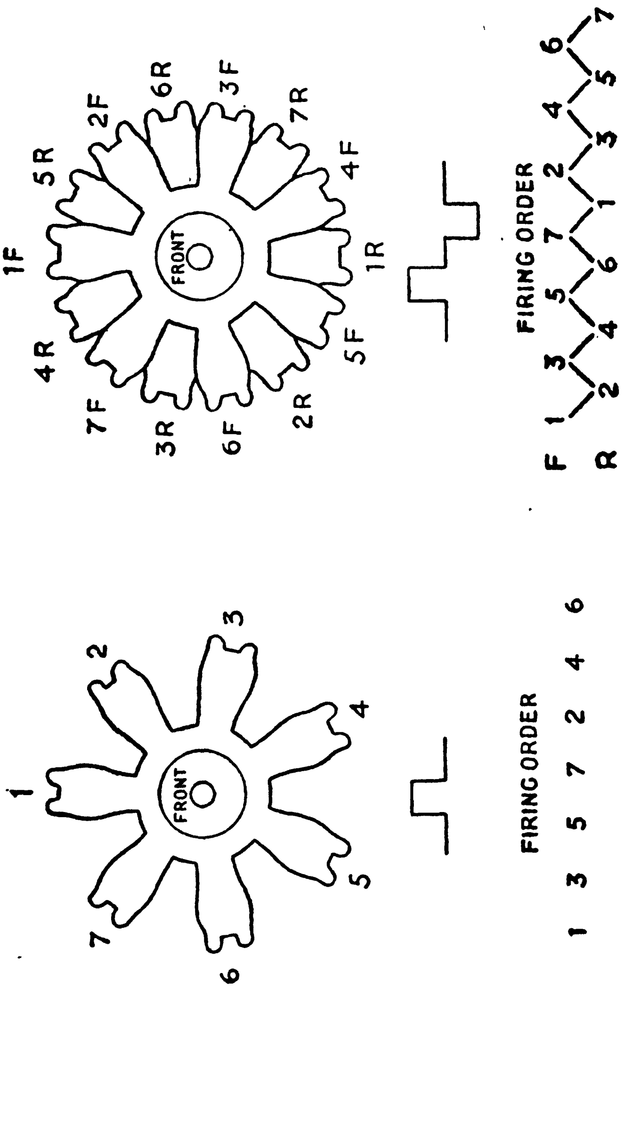


FIGURE 33
FIRING ORDER FOR SINGLE AND DOUBLE ROW RADIAL ENGINES

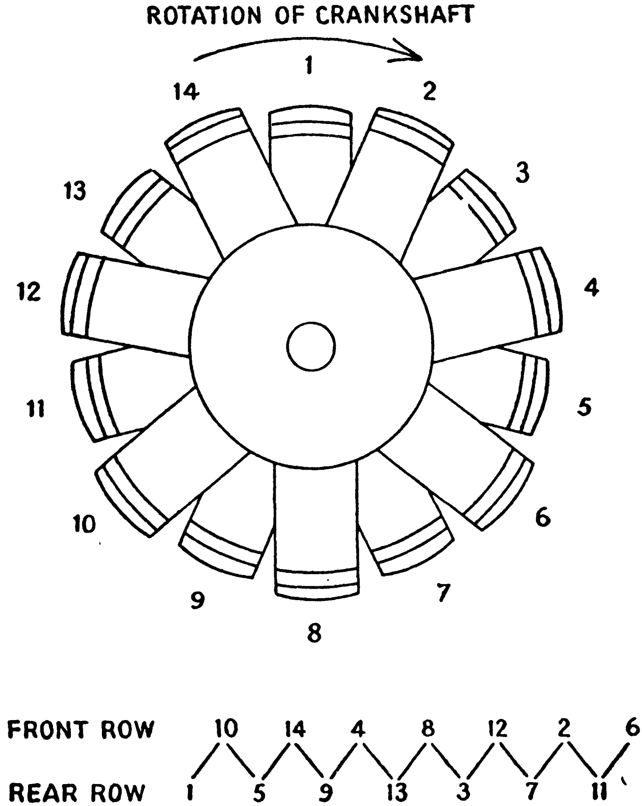
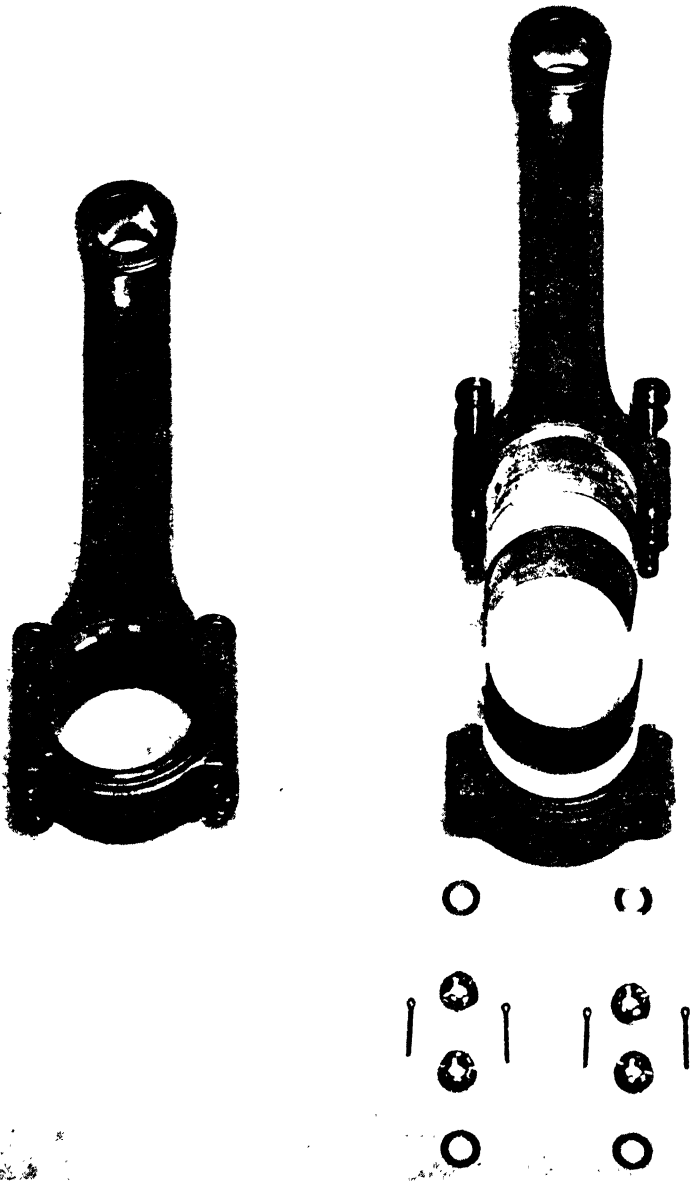


FIGURE 34
FIRING ORDER FOR "BRISTOL" 14-CYL. DOUBLE-ROW RADIAL ENGINES

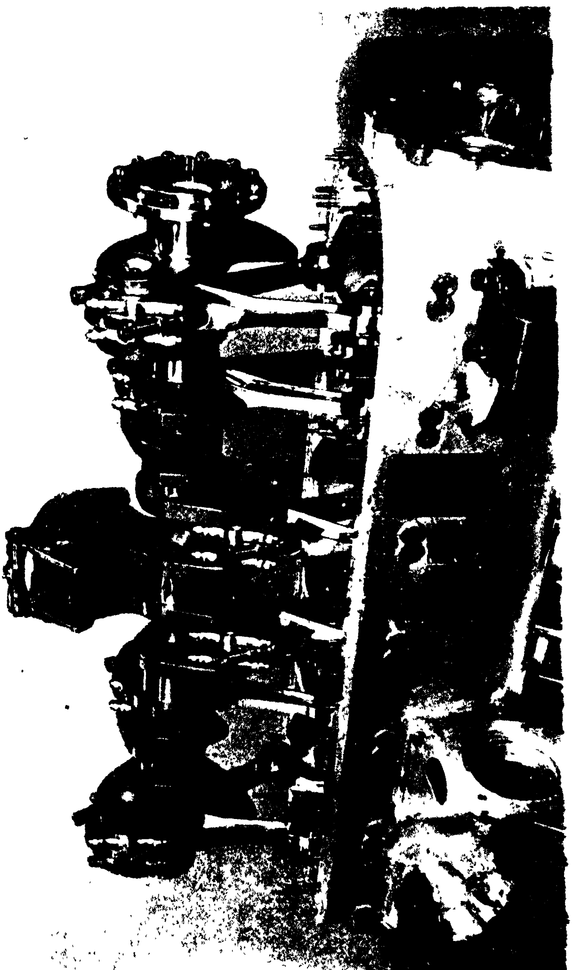
When in position on the crankpin the cap is secured by bolts and split-pinned nuts.

The gudgeon pin which secures the piston is a working fit in the small end of the rod, which, in the case of the particular rod illustrated, is not fitted with any bearing metal, as the aluminium alloy from which it is made forms a suitable bearing surface. These connecting rods of aluminium alloy are only used on engines of up to about 300 b.h.p., and are a particular feature of the D.H. Gipsy four- and six-cylinder type. (The Series 71 has a steel rod).



By courtesy of The de Havilland Aircraft Co. Ltd.

FIGURE 35 CONNECTING ROD ASSEMBLY (GIPSY MAJOR 31)



By courtesy of Rolls-Royce Ltd.

FIGURE 36

ROLLS-ROYCE MERLIN ENGINE CONNECTING ROD AND CRANKSHAFT ASSEMBLY

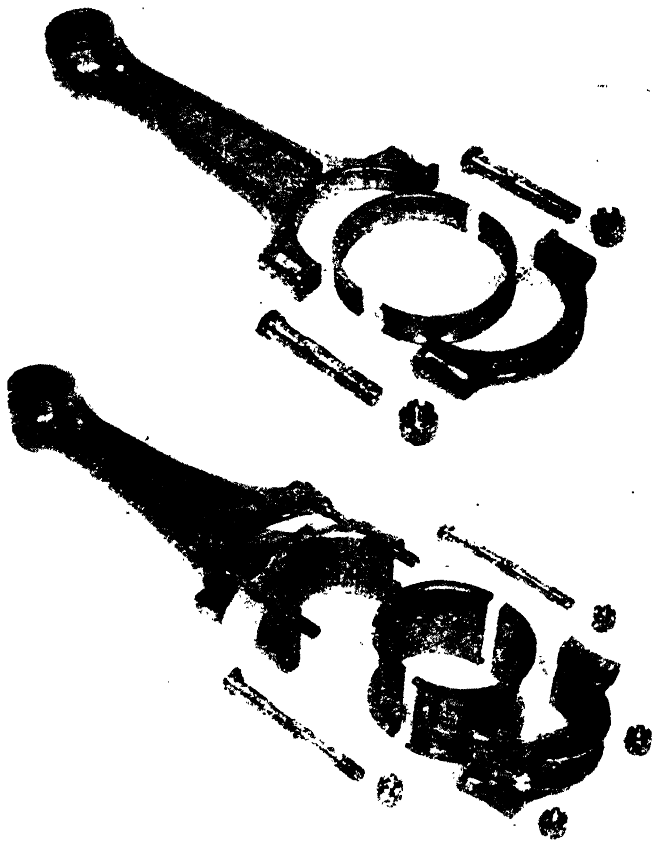


FIGURE 37 *By courtesy of Rolls-Royce Ltd.*

MERLIN XX ENGINE CONNECTING RODS DISMANTLED

When two banks of cylinders are coupled to one crankshaft, as, for example, in a Vee-twelve engine, a different arrangement is necessary in order that two big ends can operate on one crankpin.

The Merlin connecting rod (Fig. 37) is an example of such a type and consists of two rods, one of which is termed the plain rod and the other the forked rod. The forked rod is

fitted with a split steel bearing block the internal faces of which are fitted with lead-bronze bearing shells for working against the crankpin.

The external surface of the block forms the bearing surface for similar bearing shells fitted to the big end of the plain rod. When the components are assembled (Fig. 36), the necessary angular movement between the rods is provided by the plain rod working in the forked end of the other rod.

The small ends of both rods carry " floating " phosphor-bronze bushes, the bores of which provide the bearing surface for the gudgeon pin. The term " floating " signifies that the bush has a working clearance in the small end, i.e., it is not fixed. Phosphor-bronze is the usual bearing metal for small ends as it is more rigid and able to withstand the heavy pressures experienced on the small available area and to maintain its anti-friction properties at the higher temperatures prevailing in the vicinity of the piston.

Radial Engines.—The connecting-rod assembly of these engines is very different from those previously considered for in-line engines, and consists of one " master " rod, to the big end of which are jointed the remaining rods, termed " articulated " rods.

For the " Bristol " Pegasus type coupled crankshaft the assembly is as illustrated in Fig. 38. The master rod is so termed because it is the main rod steadying the whole assembly and receiving the thrusts from the articulated rods—the latter being so called because of the manner in which they are jointed to the master rod.

The " Bristol " master rod is of the solid type, i.e., it is not split across its big end, and this has the advantage of allowing a one piece big-end bush to be used instead of the split bearing shells previously mentioned.

On earlier " Bristol " engines a floating bush—having a working clearance on the crankpin and in the big end of the master rod—was used. This type of bush is shown in the big end bore of the rod in Fig. 38. On current types the big end bearing surfaces are provided by white metalled sleeves shrunk on to the crankpins.

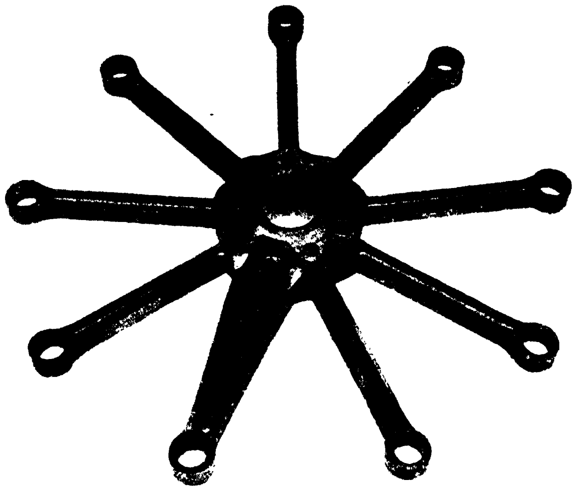


FIGURE 38 *By courtesy of The Bristol Aeroplane Co. Ltd.*

"BRISTOL" PEGASUS CONNECTING ROD AND BIG END BEARING ASSEMBLY

(On the later Hercules and Centaurus engines the big end bearing sleeve is shrunk on to the crankpin)

The solid type master rod also permits a greater number of cylinders to operate on one crankpin, as, if the big end is split, there is insufficient section left between the split and the housing for the securing pin of the articulated rod if more than seven cylinders are used. This will be apparent from a study of Fig. 38 in conjunction with Fig. 39.

The lobed flanges of the solid master rod big end are drilled to house the wrist or anchor pins upon which are mounted the articulated rods. The master rod small end and both ends of the articulated rods are bushed to provide bearing surfaces for the gudgeon and wrist pins.

When a one-piece crankshaft is used the master rod is of the split type, and this construction is used on the Armstrong Siddeley Cheetah range of engines.

The connecting-rod assembly used on the Cheetah X engine is illustrated in Fig. 39, from which it will be noted that there

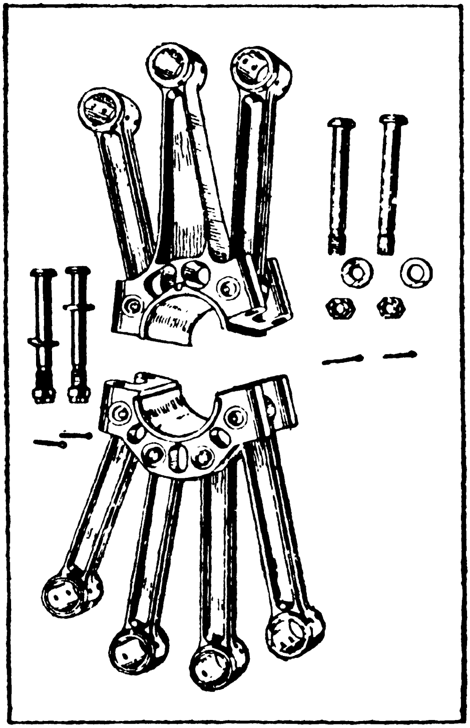


FIGURE 39 *By courtesy of Armstrong Siddeley Motors Ltd.*
CHEETAH X ENGINE CONNECTING ROD ASSEMBLY

is one master rod and six articulated rods and that the split is not across the diameter of the big end. The cap portion, which carries four articulated rods, embraces more than 180 deg., and this is necessary because, if split across a diameter, the joint would come very close to the two nearest wrist-pin housings, thereby seriously weakening the assembly.

The cap is secured to the rod by means of four bolts, and as these break into the wristpin housings nearest to the joint it is necessary to provide grooves towards each end of the four pins fitted to these housings. The bolts therefore locate the pins.

The big-end bearing is of the split steel shell type lined with lead-bronze, the wrist and gudgeon pin bushes, which are pinned in position, being of phosphor-bronze.

PISTONS

Aero engine pistons are of two general types—slipper and full-skirted.

The slipper type piston (Fig. 40) has the skirt cut away on the non-thrust faces, i.e., those faces parallel to the plane of rotation of the crank throw (at right angles to the gudgeon pin). The piston is therefore comparatively short, as it terminates just below the gudgeon pin bosses, and as the skirt is not continuous it is not possible to fit a piston ring below the gudgeon pin.

As the heat from a piston is transferred to the cylinder walls mainly via the rings, this is one reason why the slipper type is not used when high power outputs are needed. The lack of a bottom ring also brings about a tendency for the piston to "rock," due to the obliquity of the connecting rod.

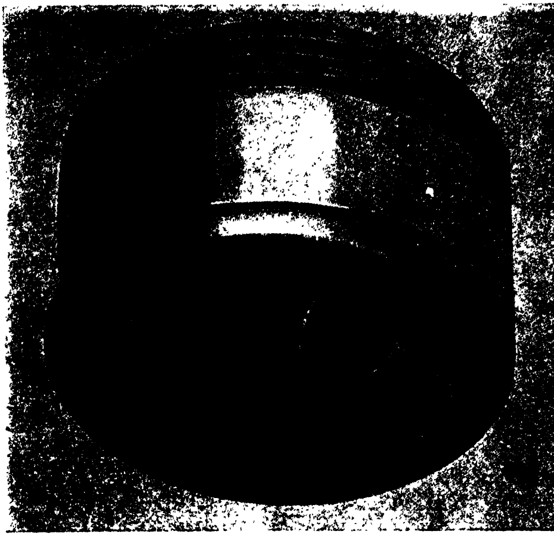
It will be noted from Fig. 40 that the thrust from the crown is taken direct to the gudgeon pin bosses, and this feature is generally retained in the design of a full-skirted piston.

Three piston rings are usually fitted, the two nearest the crown being pressure rings and the third a scraper.

Oil holes are provided either through the back of the ring groove or through a chamfer formed on the piston adjacent to the ring, for the purpose of draining oil collected by the scraper ring, to the interior of the piston.

The gudgeon pin, which is hollow, is invariably of the fully floating type, i.e., it is free to "float" in the piston bosses as well as in the small end of the connecting rod. Axial location is provided by means of circlips and washers fitted on the pin adjacent to the outside faces of the piston bosses.

Other continuous-skirted pistons are shown in Figs. 41-42, and the continuous skirt below the gudgeon pin is evident. The ring fitted in the lower portion of the skirt is of the scraper type and therefore aids in the prevention of excessive oil passing to the upper pressure rings.



By courtesy of The Bristol Aeroplane Co. Ltd.

FIGURE 41 *By courtesy of Rolls-Royce Ltd.*

(*above*) "BRISTOL" PEGASUS ENGINE PISTON

(*below*) ROLLS-ROYCE MERLIN ENGINE PISTON

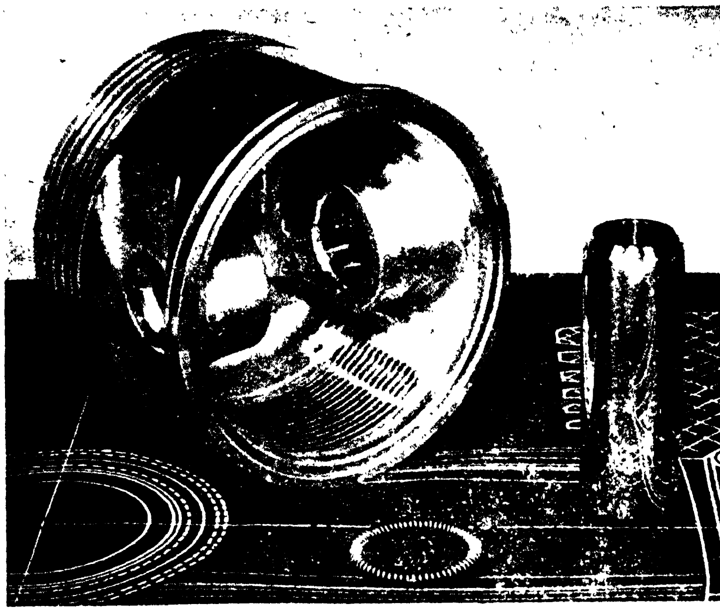


FIGURE 42 *By courtesy of Wright Aeronautical Corporation*

WRIGHT CYCLONE ENGINE PISTON

In some pistons the endwise location of the gudgeon pin is by means of circlips sprung into grooves machined internally in the piston bosses instead of by external washers and circlips, this feature being shown in the illustrations.

CYLINDER ASSEMBLIES

Owing to the amount of heat which has to be dissipated from the combustion chamber of an aero engine the cylinder head is normally made of an aluminium alloy, this metal having a much better thermal conductivity than that of steel, with which the cylinder barrel is made in the case of poppet valve engines. The complete cylinder unit is thus of composite construction, and various means are adopted for attaching the head to the barrel in order to maintain a secure and gas-tight joint.

As the aluminium alloy is not a suitable material to provide a seat for the poppet valve, it is necessary to provide seats of different material, and these are inserted in the roof of the combustion chamber.

The metal chosen for the seatings must have a similar expansion characteristic to that of the aluminium alloy, otherwise under engine operating conditions the seats would loosen in the head, even though they may have been screwed in tightly when fitted. Suitable metals for this purpose are aluminium-bronze and nickel-chromium-manganese steel, the former being more generally used in engines which do not have tetra-ethyl-lead additions to the fuel.

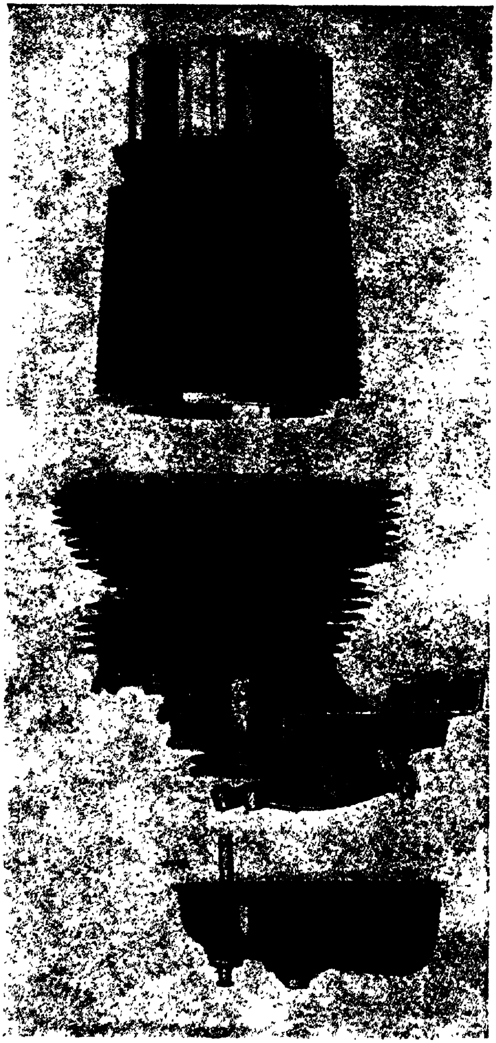
When leaded fuels are used the hot products of combustion will chemically attack the seating surfaces of both the exhaust valve and its seat, so that additional protection is needed. This is provided by welding on to the seating surfaces a very hard metal named "stellite," which is more resistant to both heat and chemical attack. Stellite is a tungsten-chromium-cobalt steel. The surfaces are subsequently ground in order to provide the necessary gas-tight joint between valve and seat.

Detachable Head Type.—With this type of construction the cylinder head is not screwed on to the barrel, but is located by a spigot on the barrel fitting into a machined recess in the head. The head and barrel are therefore easily separated for the purpose of overhaul.

The de Havilland Gipsy Series and the Blackburn Cirrus engines have cylinder assemblies of this type as shown in Figs. 43-44. In the case of the Gipsy engine the head is held to the barrel and the complete assembly held to the crankcase by means of four long steel studs which extend from the crankcase (see Fig. 60), a gas-tight joint being maintained between head and barrel by means of a copper asbestos washer.

The end of the barrel projects into the crankcase, the depth of entry being determined by the circular collar. The scallops in this collar and in the fins are to provide clearance for the holding-down studs.

The cylinder head carries one inlet and one exhaust valve, and the valve operating rockers oscillate on a spindle attached



By courtesy of The de Havilland Aircraft Co. Ltd.

FIGURE 43

CYLINDER ASSEMBLY DE HAVILLAND GIPSY MAJOR ENGINE

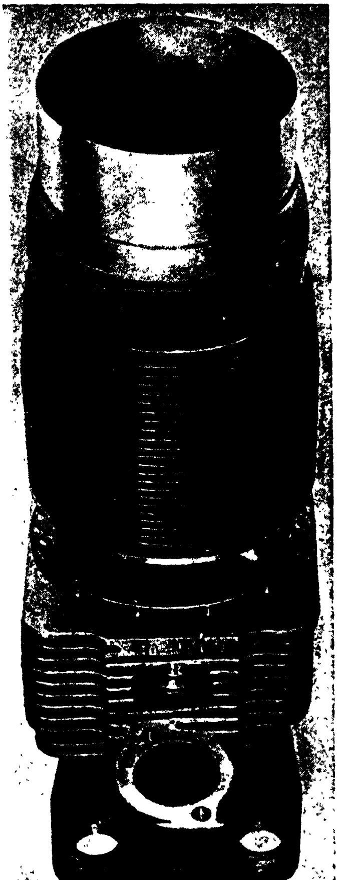


FIGURE 44 *By courtesy of Blackburn Aircraft Ltd.*

BLACKBURN CIRRUS MAJOR III
CYLINDER HEAD AND BARREL ASSEMBLY

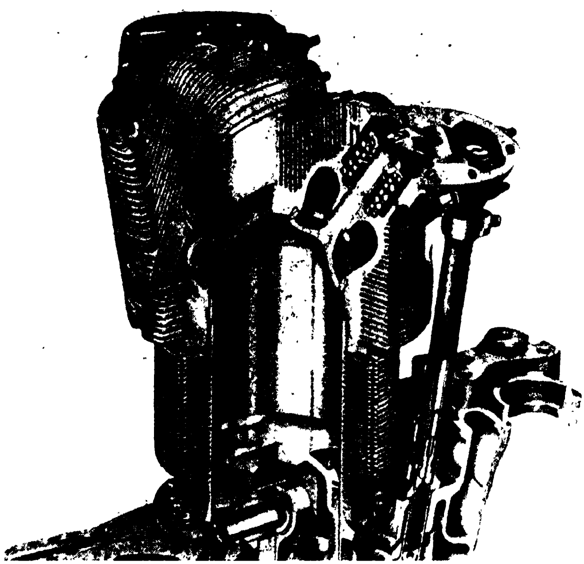
to the head by a bracket. The whole valve gear is enclosed by a cover, the lower casing of which forms an oil bath into which dip the rockers.

The cylinder head of the Cirrus engine is attached to a flange on the barrel by means of twelve studs, a laminated copper washer being interposed to form a gastight joint. Location of the parts is effected by a short spigot on the barrel

which fits into a machined recess in the head. The complete assembly is secured to the crankcase by four short studs which pass through the cylinder base flange.

Screwed-Head Type.—This type of construction is more permanent than that described above, as the cylinder head is not detachable for ordinary overhaul operations. Due to the screw thread there is good contact between the head and barrel, which facilitates heat flow.

Examples of screwed-on heads are those of the Wright Cyclone and Armstrong Siddeley engines, the assemblies being illustrated in Figs. 45 and 46.



By courtesy of Wright Aeronautical Corporation

FIGURE 45

CYLINDER ASSEMBLY OF WRIGHT CYCLONE 18 BA ENGINE

In order to ensure that the head is a very tight fit on the barrel it is shrunk on as well as being screwed, i.e., the head has to be heated and thus expanded before it is possible to screw it on to the barrel. When cold it contracts and therefore

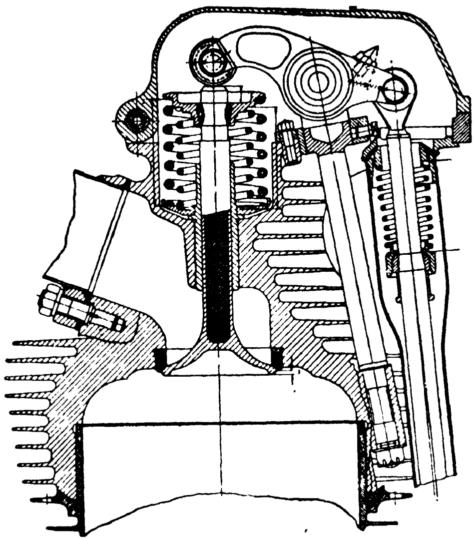


FIGURE 46 *By courtesy of Armstrong Siddeley Motors Ltd.*
CROSS-SECTION OF CYLINDER HEAD, CHEETAH X ENGINE

grips the barrel very firmly, and when heated by subsequent engine running it does not become loose.

In order to provide additional security against loosening due to the different expansions of aluminium alloy and steel the Cheetah cylinder has a steel ring screwed on to the cylinder barrel prior to the head. When the head is in position this ring, which is formed with a chamfer, is screwed up against a similar chamfer on the underside of the head. Under engine operating conditions the head, expanding more than the steel ring, tends to climb up the chamfer, thus effectively locking the screw threads. The steel ring is formed as a fin, in which holes are drilled for the special tightening spanner.

An interesting feature of the Cheetah type cylinder is that it is not attached to the crankcase by means of a base flange and studs, but by being screwed into an adaptor located in the crankcase aperture (Fig. 47). When in position it is firmly held by means of a chamfered steel locking ring which, when tightened, exerts a wedging action between the cylinder socket

and a collar on the cylinder barrel. This action tends to draw the cylinder out of its aperture, and the cylinder being screwed into the adaptor, the flanged end of this is pulled hard against a seating inside the crankcase, thereby firmly securing the assembly.

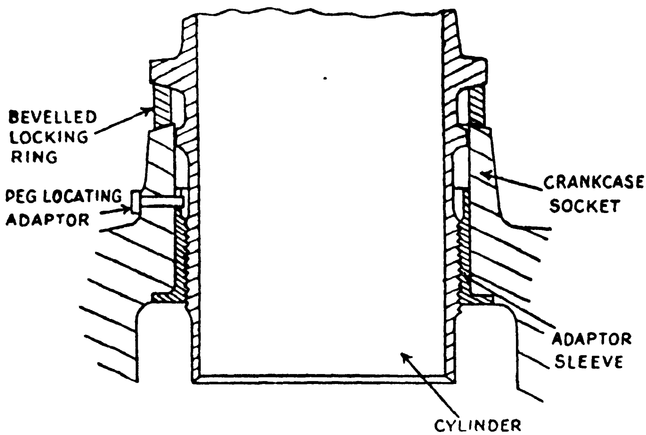
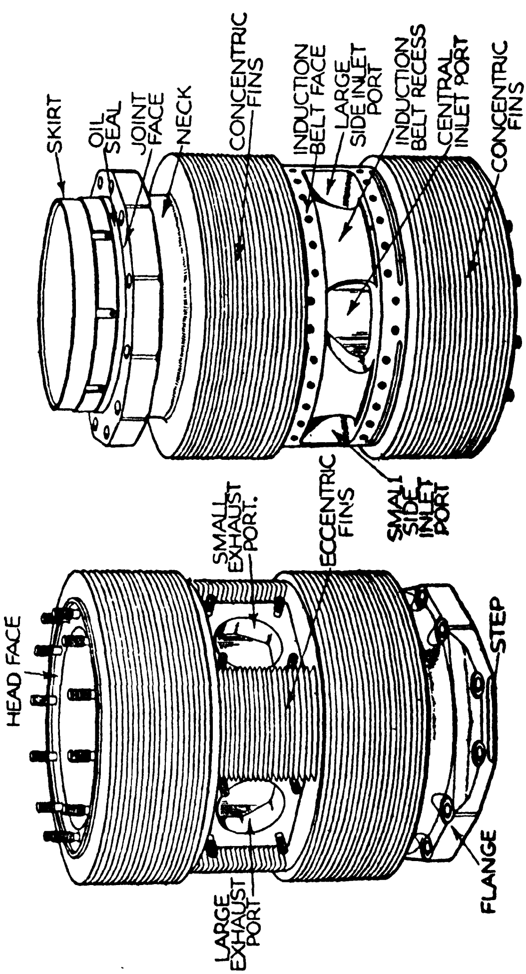


FIGURE 47

CYLINDER TO CRANKCASE ATTACHMENT
ARMSTRONG SIDDELEY CHEETAH ENGINE

Sleeve-Valve Engine Cylinder.—Due to the sleeve-valve method of operation, the construction of the cylinder assembly differs in many respects from that employed when poppet valves are fitted. There is a cylinder head (often termed a junkhead) and a barrel, but the design is fundamentally different to those previously described.

In the "Bristol" construction both the barrel and the head (Figs. 48, 49) are made of aluminium alloy, the valve ports being machined in the former, there being three induction ports embraced by a common manifold and two separate exhaust ports. The head, which is somewhat similar in appearance to a flanged inverted piston, is secured to the top of the barrel by studs and nuts, and protrudes into the bore of the sleeve valve, which is a sliding fit in the bore of the barrel, this arrangement being shown in Fig. 49. It will be apparent that the face of the junkhead forms the roof of the combustion chamber.



By courtesy of Aircraft Production

FIGURE 48

"BRISTOL" SLEEVE-VALVE CYLINDER BARREL

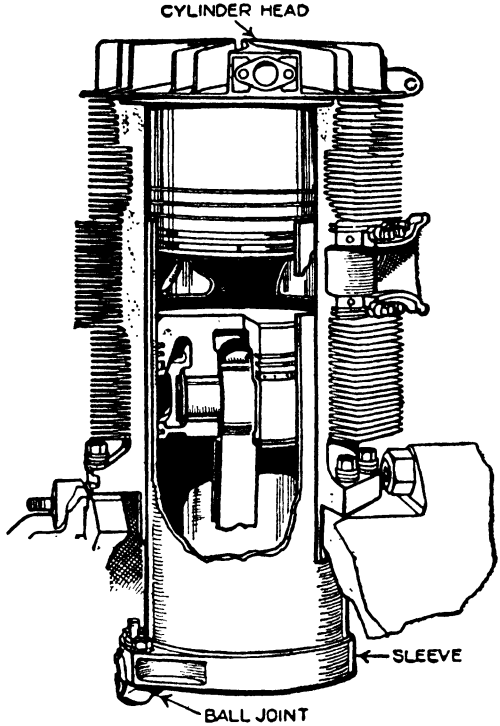
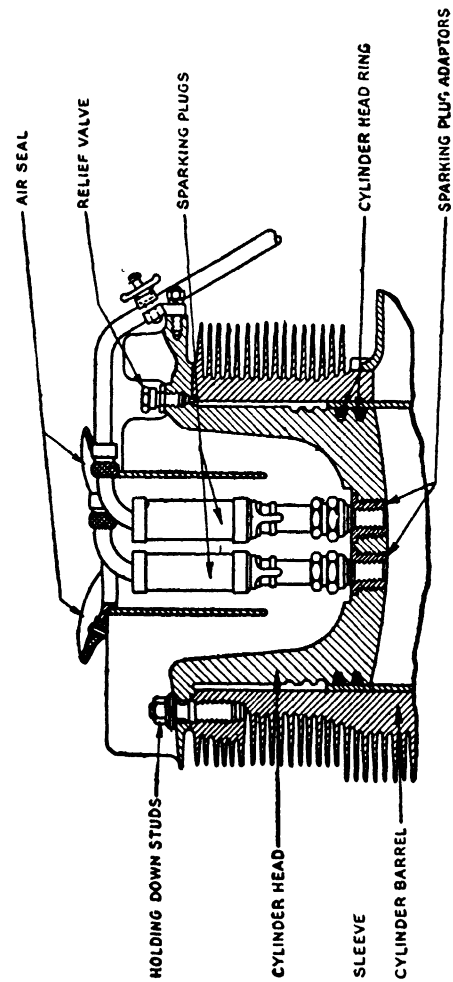


FIGURE 49 *By courtesy of* Aircraft Production
"BRISTOL" SLEEVE-VALVE ENGINE,
CYLINDER-HEAD AND SLEEVE ASSEMBLY

The two sealing rings fitted in the head are for the purpose of providing a gas seal during the high-pressure periods of the compression and firing strokes when the sleeve reaches the top of its path and its ports rise above the rings. Adaptors fitted in the centre of the head are for the sparking plugs.

Due to the inverted piston formation of the junkhead there is a deep external recess, and provision has to be made for its cooling. This takes the form of special finning and a head cowl, by means of which the air is deflected into the pocket, over cooling fins, and out at the rear.

The sleeve valve is actuated by means of a ball coupling which engages a small crank driven at half engine speed,



By courtesy of The Bristol Aeroplane Co. Ltd.

FIGURE 50

"BRISTOL" SLEEVE-VALVE ENGINE — SECTIONAL VIEW OF HEAD

and its combined reciprocating and semi-rotary movement causes the ports to traverse the corresponding ports in the cylinder barrel once every two crankshaft revolutions as for the four-stroke cycle (see also page 83 and Figs. 57, 58).

To minimize oil consumption a special form of scraper ring is fitted in the cylinder barrel in a groove machined adjacent to the base flange. This ring contracts on to the sleeve valve, thus providing the seal, and oil collected is drained to the crankcase by holes drilled through the barrel spigot beneath the ring.

Liquid-cooled Engine.—Modern practice is to use a type of construction in which the cylinder liners are inserted in a

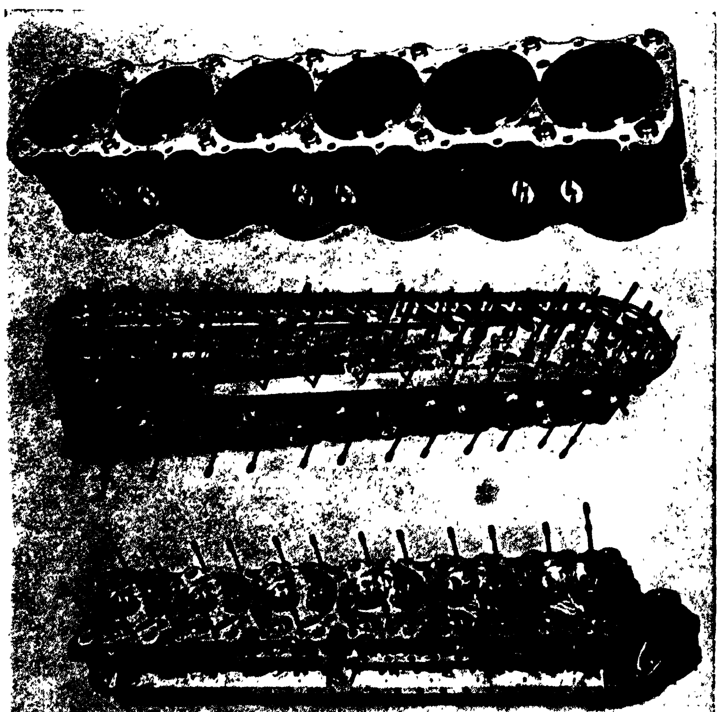


FIGURE 51 *By courtesy of Rolls-Royce Ltd*

ROLLS-ROYCE GRIFFON 65, CYLINDER BLOCK AND HEAD

common light alloy casting, the complete unit being termed a monoblock.

Rolls-Royce Merlin and Griffon engines have this type of cylinder assembly, and details of the construction are illustrated in Figs. 51, 52.

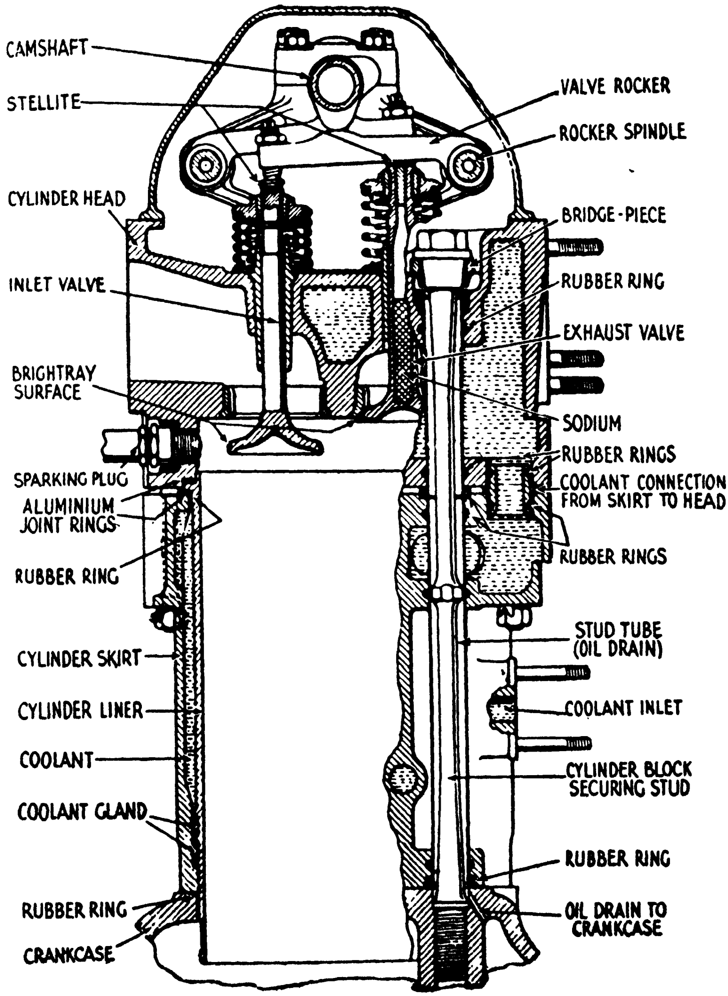


FIGURE 52 *By courtesy of* Flight

SECTIONAL VIEW OF GRIFFON 65 CYLINDER BLOCK

The individual combustion chambers are formed in the head portion of the casting, and the six steel cylinder liners are inserted in the block and retained in position when the complete block is pulled down on to the crankcase by means of fourteen long studs. Aluminium washers compressed each side of the small flange at the top of the liner provide a gas-tight joint. For additional security the head is tied to the cylinder block by a series of studs whose nuts pull up against a flange formed at the top of the block casting.

To provide a liquid-tight joint at the base of each liner where it passes through the casting, each liner carries a special spring-loaded gland ring located in a groove machined on its external surface. Passages for the cooling liquid are provided along the head of the casting as well as around the liners.

There are four valves per cylinder, the valve seats being screwed and shrunk into the roof of the combustion chamber, and an overhead camshaft and rocker spindles are carried in bearings secured to the top of the block.

An aluminium alloy cylinder block of the Napier Sabre sleeve-valve engine is illustrated in Fig. 53.

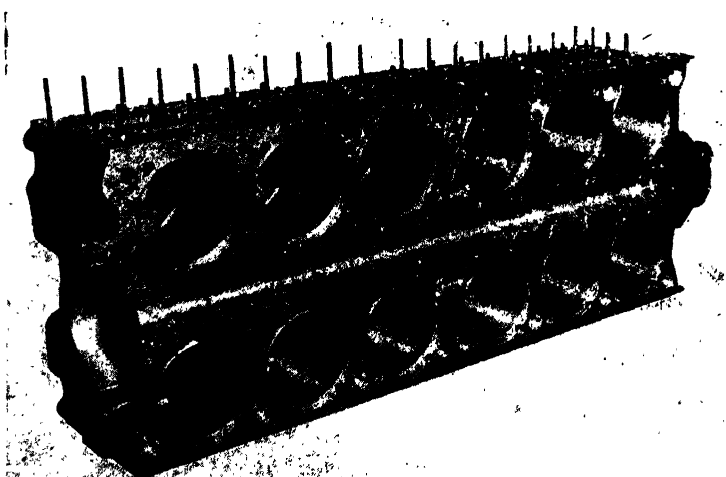


FIGURE 53 *By courtesy of D. Napier & Son Ltd.*

CYLINDER BLOCK OF NAPIER SABRE SLEEVE-VALVE ENGINE

The twelve cylinder bores each contain three inlet and two exhaust ports, the latter facing inwards so that each pair of cylinders (one top and one bottom), deliver into a common passage to the outer face of which is secured the exhaust stub. There is not of course a steel liner in the cylinder bores ; the steel sleeve-valves bear directly on the aluminium alloy. Separate heads are provided for each cylinder, a rubber joint ring forming the seal. Passages are formed in both cylinder block and head for circulation of the coolant.

SODIUM-COOLED VALVES

As the power output of aero engines increased due to progressive design, supercharging, leaded fuel, etc., a serious limitation was imposed by the inability of the ordinary exhaust valve to operate under the arduous conditions imposed on it by the amount of heat ejected and chemical attack by the products of combustion. As mentioned previously, " stellited " valves are used to enable the seating surfaces to withstand these conditions, but in addition it became necessary to provide means for extra cooling of the valve, particularly on air-cooled engines.

This additional cooling is accomplished by making the valve stem, or part of the head and stem, hollow, and partly filling with metallic sodium, or a sodium-mercury eutectoid liquid at room temperature which, with the valve in operation, melts and, surging up and down, transfers a great amount of heat from the head to the stem of the valve and so to the guide and cylinder head, where added finning can be provided to dissipate the heat. Sodium, having a melting point of 97 deg. C., a boiling point (at 760 mm. pressure) of 750 deg. C., and good thermal conductivity, is a very suitable material for the purpose.

After filling, the ends of the valve stems are closed and fitted with the hardened tip against which the rocker striking pad operates. This hardened tip is necessary, as the only alloy steel suitable for the valve is relatively soft and will not withstand the hammering action of the rocker pad.

VALVE OPERATING MECHANISMS

For poppet-valve engines the basic parts of the operating mechanism are cams and push rods, and tappets or rockers according to the engine design.

The valves of engines working on the four-stroke principle need actuating once in every cycle of operations, i.e., four strokes or two crankshaft revolutions so that where one cam only is provided to operate each inlet valve and one cam only for each exhaust valve per cylinder, then the camshaft must be driven at one-half crankshaft speed. In this manner, when the crankshaft has completed two revolutions (four strokes) the camshaft will have made one revolution, and therefore the inlet and the exhaust cam carried on the shaft will have operated their respective valves once only as required.

All in-line engines have similar camshafts, so that the gearing between the crankshaft and the camshaft will be in the ratio 2 to 1.

Tappet, Push Rod and Rocker Type.—Engines in which the camshaft (or its equivalent) is carried inside the crankcase utilize tappets and push rods in order to convey the cam motions to the rocker which operates the valves. An example of this construction is given in Fig. 54, which shows the arrangement for the Wright Cyclone 14 cylinder radial engine.

In this particular assembly pressure lubrication of the mechanism is obtained by metering a supply of oil through the valve tappets and guides, into the push rods and through holes on the adjusting screws into the rocker arm bearings.

With a normal rocker assembly provision is made to adjust the valve clearance, i.e., the small gap left between the end of the valve stem and the striking part of the rocker, when the tappet is on the base circle of its cam. This clearance is necessary to ensure that the valve is not prevented from seating properly during that part of the cycle of operations when it should be closed. A screw in either the push rod or valve end of the rocker is the usual means of adjustment. On the Armstrong Siddeley Cougar engine, however, a self-adjusting hydraulically operated tappet is employed, by means of which

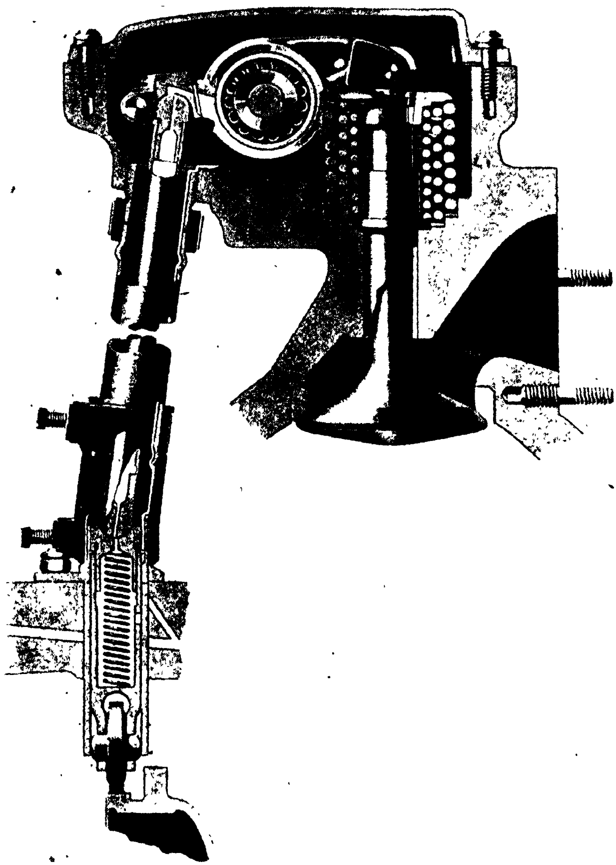


FIGURE 54 *By courtesy of Wright Aeronautical Corporation*

DIAGRAMMATIC VIEW OF VALVE OPERATING MECHANISM — WRIGHT CYCLONE 14-CYLINDER ENGINE

the clearance is maintained practically zero, any alterations due to expansion, etc., being automatically compensated by the hydraulic action.

Radial Engines.—The poppet-valve radial engine has what is called a cam drum or cam sleeve in place of the camshaft

used for the in-line engine. This cam drum has two adjacent " tracks " each carrying equally spaced cams for operation of the inlet and exhaust tappets respectively of *all* the cylinders.

In one complete revolution of the cam drum each cylinder inlet and exhaust tappet will therefore be acted upon, and as only one such actuation is needed for each two crankshaft revolutions the cam drum must rotate at crankshaft speed divided by the number of cams. The tappet and cam drum

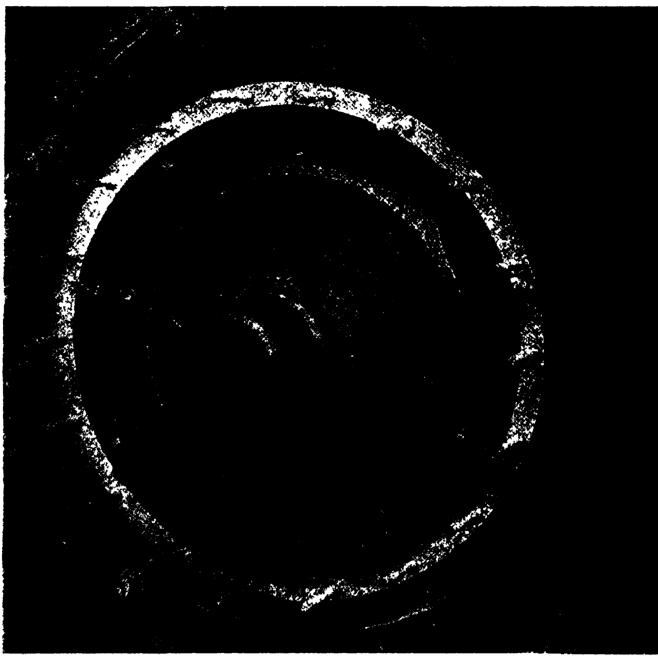


FIGURE 55 *By courtesy of The Bristol Aeroplane Co. Ltd.*

CAM SLEEVE AND TAPPET ASSEMBLY OF "BRISTOL" PEGASUS POPPET-VALVE ENGINE

assembly of a " Bristol " engine is shown in Fig. 55. In the Wright Cyclone engine the motion of the tappets is transferred to the valve gear as illustrated in Fig. 54.

Overhead Camshafts.—The term " overhead " when applied to a camshaft means that it is located along the cylinder heads

instead of in the crankcase, and this form is very convenient for in-line type engines.

The overhead camshaft is carried in bearings secured to the cylinder head or to the cylinder block casting and receives its drive either from the front or the rear end of the engine by means of a single shaft. The tappets and push rods previously mentioned are not required as the valves can be operated on directly by the rocker arms.

When in-line engines have four valves per cylinder, one method is to provide two exhaust and two inlet cams for their operation. This may be carried out either by the employment of twin camshafts, each of which operates one exhaust and one inlet valve per cylinder, or by a single central camshaft carrying the four cams per cylinder and operating the valves through rocker arms.

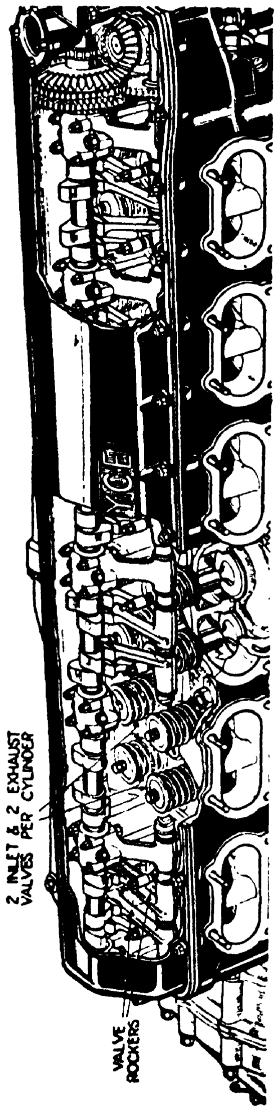
The Rolls-Royce Merlin and Griffon camshaft assemblies are of the latter type, and the cams operate rocker arms which oscillate on spindles mounted each side of the camshaft. Details of this arrangement are illustrated in Figs. 52 and 56.

Another method is to employ a forked rocker arm for operation of two valves from one cam, and this type was used on the American Allison engine. (See Fig. 68).

Sleeve-Valve Operation.—In place of the usual cam, tappet, push-rod and rocker mechanism associated with poppet valves, the " Bristol " sleeve-valve engine has a simple train of gears driven from the crankshaft by means of which a number of small cranks (one per sleeve-valve) are driven at half crankshaft speed. Each crankpin engages, through a spherical and sliding coupling, a lug on the base flange of its appropriate sleeve valve, so that rotation of the crank causes the sleeve to have a motion which combines reciprocation and partial rotation.

In the sleeve are four ports of special shape—two inlet, one exhaust, and one common port serving in turn as an inlet and an exhaust.

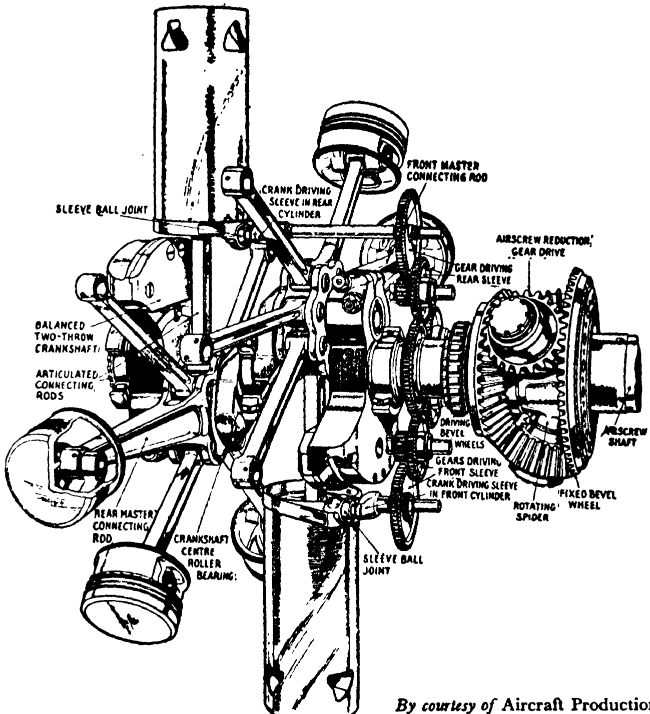
In the cylinder barrel are three inlet ports and two exhaust ports, and at the correct periods in the cycle of operations those



By courtesy of Aircraft Production

FIGURE 56

DETAILS OF CAMSHAFT ASSEMBLY — MERLIN ENGINE



By courtesy of Aircraft Production

FIGURE 57
"BRISTOL" SLEEVE-VALVE ENGINE SHOWING VALVE-OPERATING MECHANISM

in the sleeve traverse the appropriate ports in the barrel, thereby enabling the charge to enter or the exhaust to be ejected as the case may be (Fig. 58).

The combined reciprocation and partial rotation of the sleeve will cause its ports to travel in an elliptical path, so that the inlet and exhaust ports in the cylinder are only uncovered by the corresponding sleeve ports once in every complete cycle of the sleeve-valve. As the sleeve is driven at one-half engine speed, this cycle will be completed once in every two revolutions of the crankshaft, i.e., valve operation as for the normal four-stroke cycle.

During the high-pressure periods of the cycle the sleeve ports are shielded by the junkhead, the sleeve passing up

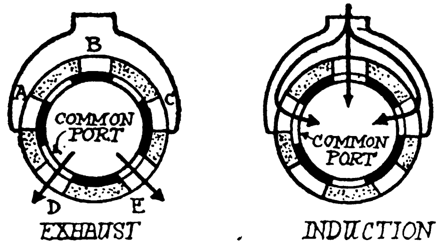


FIGURE 58 The Aeroplane *Copyright*

SLEEVE-VALVE MOVEMENT FOR EXHAUST AND INDUCTION

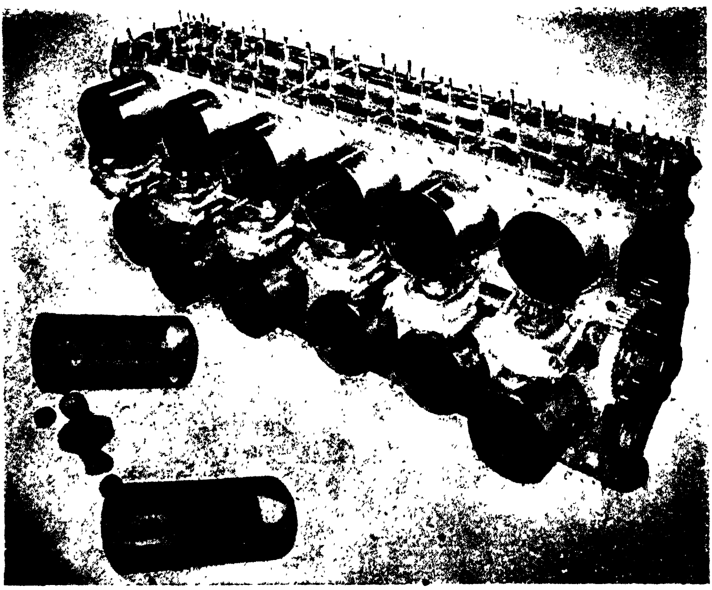


FIGURE 59 *By courtesy of D. Napier & Son Ltd.*

NAPIER SABRE ENGINE — SLEEVE-VALVE DRIVE

into the annular space between the head and cylinder barrel as shown in Fig. 49..

The Napier Sabre sleeve-valve drive, (Fig. 59), is taken from the top crankshaft front pinion on each side, through idler spur gears to a hollow shaft which runs in bearings

formed along the inner face of the cylinder block and the securing caps.

The complete hollow shaft, (which is in two halves coupled at the centre with a splined sleeve), has six integral worm gears for driving the worm wheels which are secured to the sleeve cranks. These cranks, arranged at 180 deg. rotate in two roller bearings (one each side of the worm wheel), mounted in pedestals which also form the caps of the drive shaft bearings. The worm wheel is bolted to a flange on the crank shaft, the attachment holes providing a vernier adjustment for sleeve timing. The complete assembly shown in Fig. 59 is secured to the cylinder block face of the crankcase.

In the sleeve are four ports—two inlet, one exhaust and one common port which is used alternatively for inlet and exhaust.

The helical grooves on the inside of the sleeve at the inner end assist the removal of excess oil. The driving pin which engages the crank through a ball joint is integral with a thickened band at the end of the sleeve.

THE CRANKCASE

The crankcase, is the foundation upon which the other components are erected in order to form the complete engine, and for aero engines it is made of an aluminium or magnesium alloy, the former being more generally employed.

The form of crankcase used is of course dependent upon the type of engine, but the general characteristics of all crankcases for in-line engines are similar, as are those for the radial engine type.

As an example of the type of crankcase used for a single row of in-line cylinders, that for the Gipsy Major 31 is illustrated in Fig. 60.

The main bearings which support the crankshaft are carried by substantial crosswebs, which also stiffen the crankcase, the bearing housings for the camshaft being also formed in these webs.

The bearing caps, which are detachable for the purpose of placing the crankshaft in position, have been removed in the illustration.

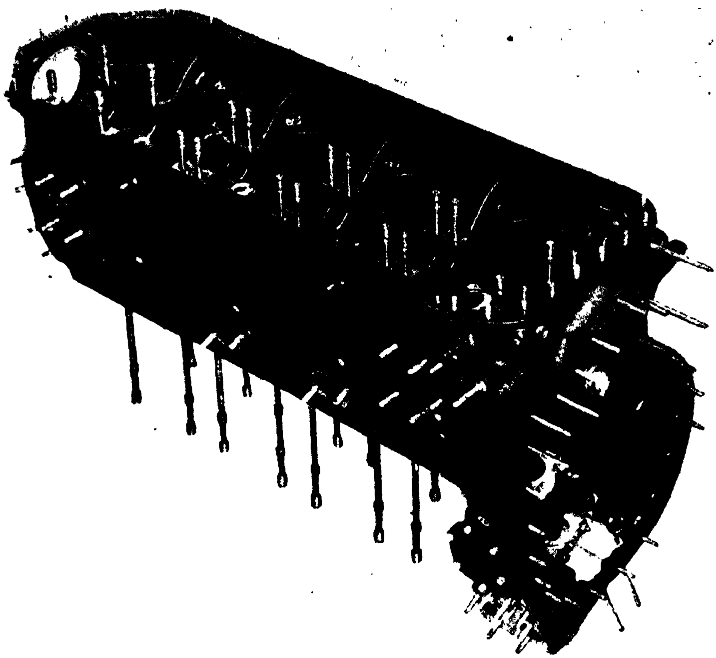


FIGURE 60 *By courtesy of The De Havilland Aircraft Co. Ltd.*

GIPSY MAJOR 31 CRANKCASE

The top cover is, as its name implies, used to enclose the internal parts of the engine, and in addition it has facings for the purpose of mounting various auxiliaries as, for example, those shown in Fig. 7. The tapered front end is formed with a housing which is utilized to secure the ball thrust race carried at the forward end of the crankshaft.

For the Vee-twelve the type of crankcase is as shown in Fig. 61. There are seven main bearings to carry the six-throw crankshaft and the cylinder apertures are on facings which carry the blocks at an included angle of 60 deg. The front end also incorporates the rear half of the casing which houses reduction gearing.

The Napier Sabre is fitted with a crankcase split along the vertical centre line of the engine, and one half of the crankcase

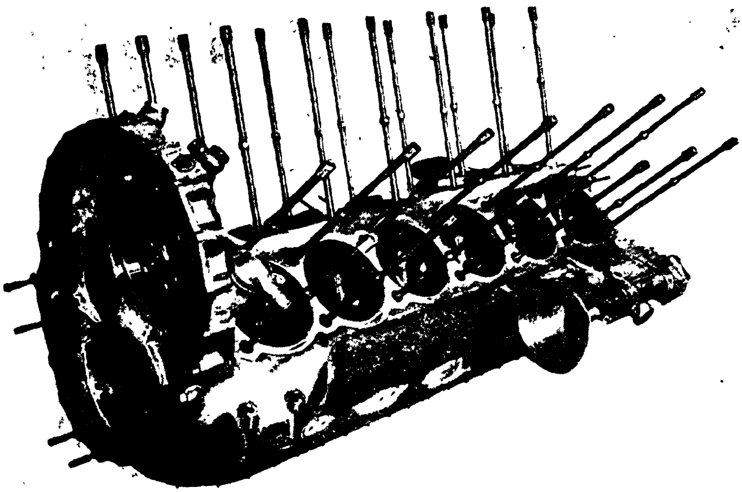


FIGURE 61 *By courtesy of Rolls-Royce Ltd.*

ROLLS-ROYCE MERLIN XX CRANKCASE

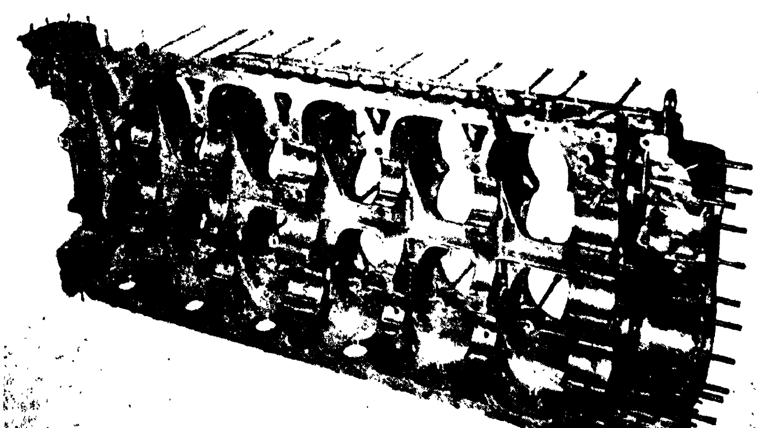


FIGURE 62 *By courtesy of D. Napier & Son Ltd.*

NAPIER SABRE HALF CRANKCASE — INSIDE VIEW

is illustrated in Fig. 62. Housings for the two six-throw crankshafts are formed along each side of the crankcase.

Radial engines have a circular type crankcase either formed in one piece like those for Armstrong Siddeley engines or split across the cylinder apertures like the " Bristol " type (Fig. 63) and Wright Cyclone double-row engine (Fig. 64).

Unlike in-line engines, which have anti-friction metal main bearings, the crankshaft of a radial engine is carried upon large roller bearings housed in the walls of the crankcase, the front end or propeller shaft being further supported by a ball thrust type bearing.

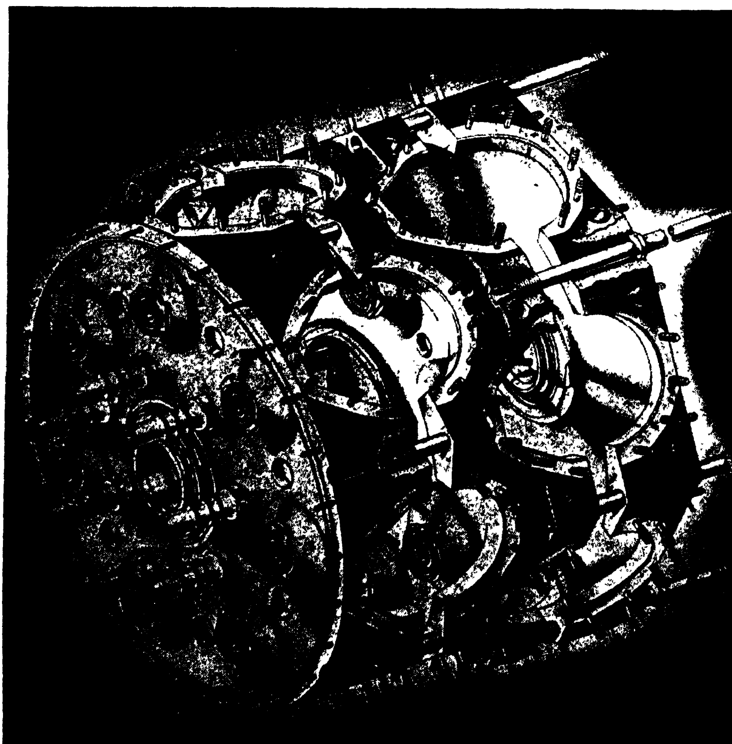


FIGURE 63 *By courtesy of The Bristol Aeroplane Co. Ltd.*

CRANKCASE ASSEMBLY OF "BRISTOL" HERCULES SLEEVE-VALVE ENGINE

Although the primary object of a crankcase is to carry the crankshaft and cylinder assemblies, there are other essential components which form extensions to the crankcase proper. For in-line engines there is usually a separate casing attached to the rear and termed the rear cover, timing gear cover, or wheelcase. This casing contains the gear drives to the pumps, supercharger, etc., and other accessories. Attached to the back of the rear cover is the characteristic circular casing of the supercharger, which also carries the carburettor.

In radial engines the positions of the rear cover and supercharger are reversed, as the supercharger unit is attached to the rear of the crankcase and the rear cover to the supercharger casing.

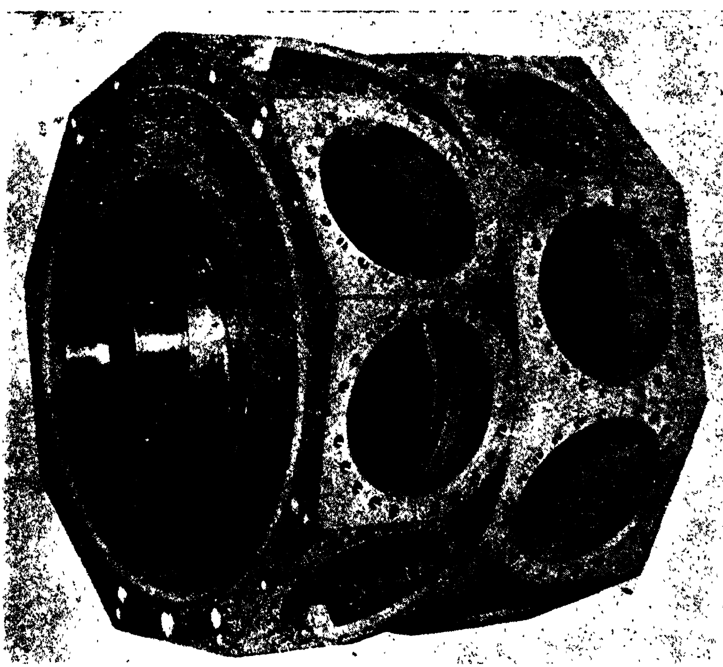


FIGURE 64 *By courtesy of Wright Aeronautical Corporation*

STEEL MAIN CRANKCASE SECTION OF WRIGHT CYCLONE 18-CYLINDER ENGINE

At the front end (and sometimes the rear) of the crankcase proper the radial engine carries its cam gear and tappet assembly, followed by the reduction gear and its casing, while the in-line engine has the reduction gear and casing only. Where no reduction gearing is fitted the forward end is closed by a ront cover.

REDUCTION GEARING

The need for reduction gearing between the engine crank-shaft and propeller shaft has been mentioned previously, and some of the types in use will now be briefly explained.

FIGURE 65 *By courtesy of Rolls-Royce Ltd.*

ROLLS-ROYCE MERLIN LAYSHAFT TYPE REDUCTION GEARING

In-line Engines.—The layshaft type reduction gear as used on Rolls-Royce Merlin and Griffon engines is illustrated in Fig. 65, from which it will be seen that the reduction is effected by direct meshing of two spur gears. The pinion is separately mounted on roller bearings and is driven by a short coupling shaft which engages with the internally toothed annulus fitted to the front end of the crankshaft as shown in Fig. 24. The internally toothed ring visible in this illustration is itself meshed with the annulus to provide a semi-floating drive. The coupling shaft is splined at its forward end to engage with the splined bore at the front of the pinion. This type of construction relieves the gearing from crankshaft torsional vibrations and end float effects.

The normal Merlin engines are right hand tractors but the Merlin 131 is made left hand by the introduction of an idler gear between the normal pinion and propeller shaft gear as shown in Fig. 66.

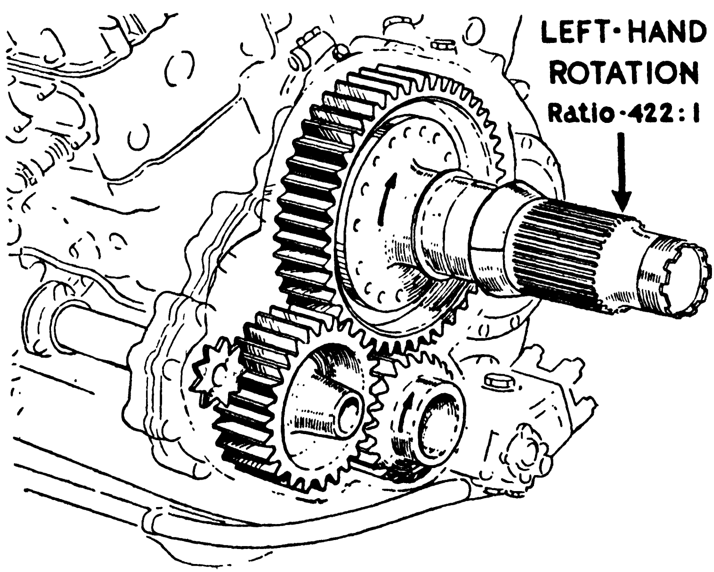


FIGURE 66 *By courtesy of Rolls-Royce Ltd.*

GEARING FOR LEFT-HAND ROTATION OF MERLIN 131 ENGINE

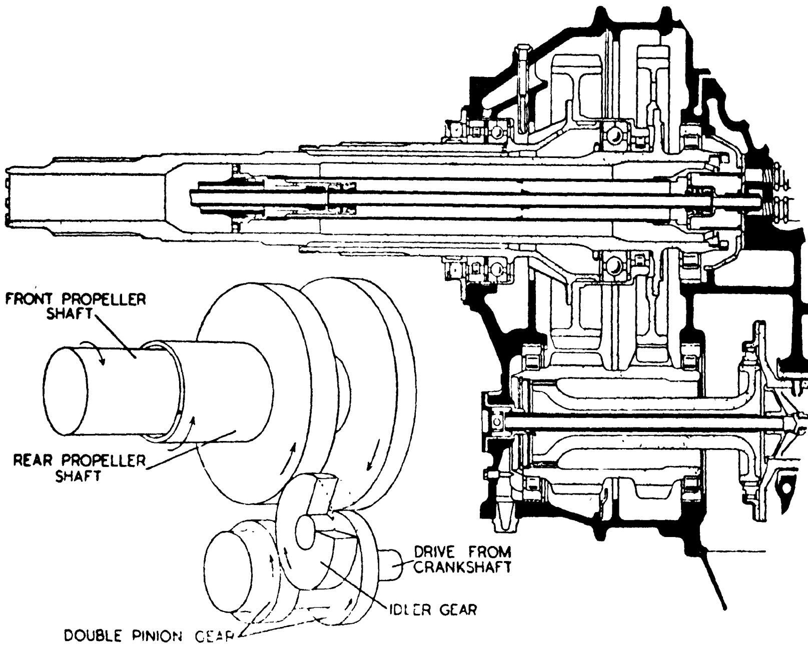
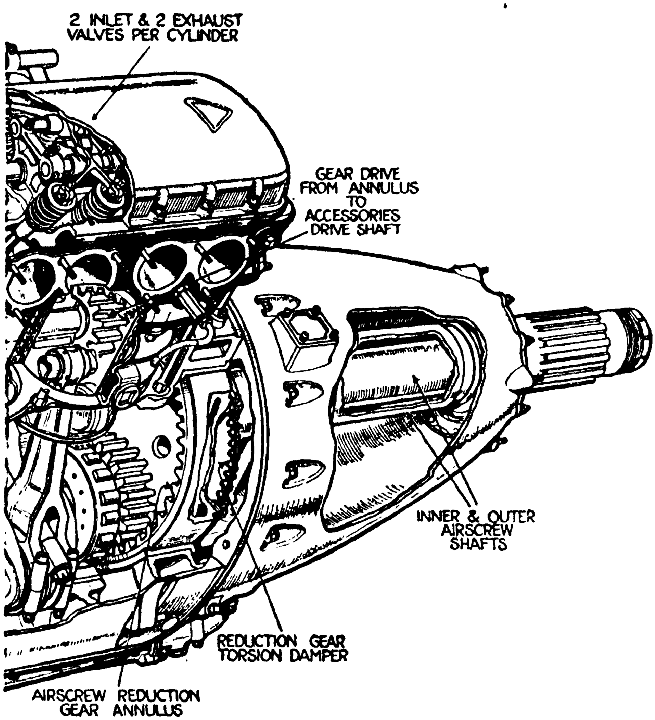


FIGURE 67 *By courtesy of Rolls-Royce Ltd.*

REDUCTION GEAR ASSEMBLY FOR COUNTER-ROTATING PROPELLERS, ROLLS-ROYCE GRIFFON 83 ENGINE

Fig. 67 shows the special assembly fitted to the Griffon 83 for driving a counter-rotating propeller. The two shafts are mounted co-axially, the drive to each being taken from a double pinion which is coupled to the crankshaft as described above. The forward end of the inner shaft is located and supported by a bearing carried in the front of the hub of the rear propeller unit. This bearing is positioned on the inner shaft just forward of the outer shaft on the stepped portion which can be seen in the cross-section.

Another interesting construction was that of the American Allison C15 engine (Fig. 68), in which the pinion drives an internal or annulus gear, the hub of which is splined to the propeller shaft proper, whose forward end is supported by a ball thrust type bearing, while the flanged rear end is coupled to the inner shaft by a plate-type frictional damper in front



By courtesy of Aircraft Production

FIGURE 68

ALLISON C15 ENGINE REDUCTION GEAR

of the annulus. The object of this damper is to minimize torsional fluctuations being transmitted from the crankshaft to the propeller.

The twin crankshaft Napier Sabre engine has a compound reduction gear drive to the propeller shaft as illustrated in Figs. 69 and 70. The spur pinion at the front end of each crankshaft meshes with two layshaft gears, each layshaft having a helical gear at its front end. All four helical pinions mesh with the aïrscrew shaft gear to give an overall reduction ratio of 0.2742 to 1.

A special feature of the assembly is the balancing device fitted to equalize the loading from each crankshaft to its pair of compound gears. Each layshaft is permitted a limited end

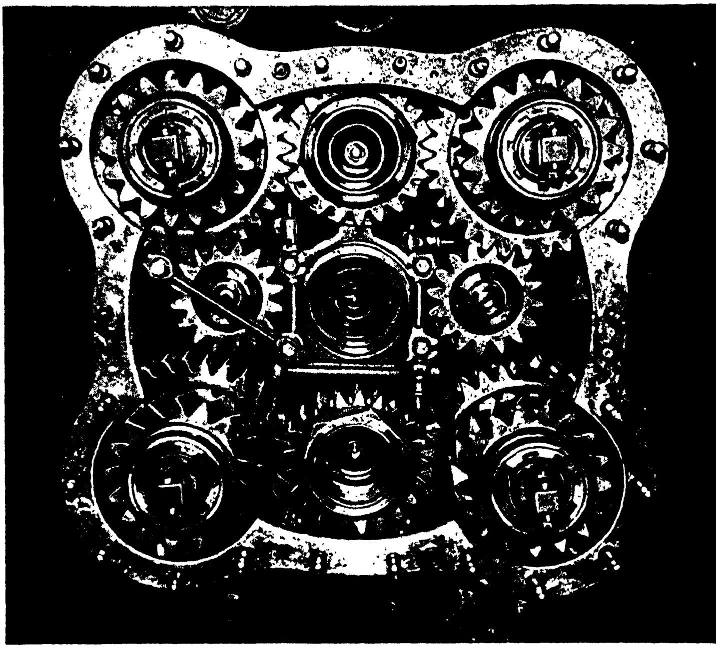


FIGURE 69 *By courtesy of D. Napier & Son Ltd.*

NAPIER SABRE COMPOUND REDUCTION GEARING

float which is controlled by twin balance arms fitted as shown in Fig. 70, each arm being centrally pivoted on a forked pillar anchored to the front casing. The ends of each arm are yoked to tubular shafts carried by ball races in the bores of the hollow layshafts, the shaft float being damped by spring loaded plungers acting between the end of the shaft and the front casing.

In the event of increased loading the helical gear receiving the load will, due to the tooth inclination, tend to ride forward out of mesh with the propeller shaft gear, thereby diminishing its loading. At the same time, due to the balance arm the other layshaft with its helical gear will be pressed backwards into mesh until the loading is balanced again.

The permitted layshaft float is small (0.020 in.), and in practice the device can be regarded as a floating mounting

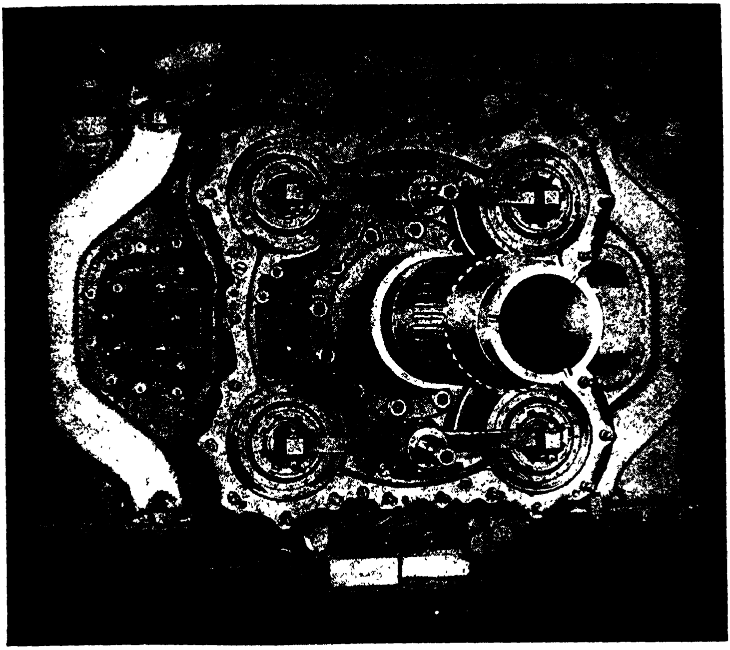


FIGURE 70 *By courtesy of D. Napier & Sons Ltd.*

NAPIER SABRE REDUCTION GEARING SHOWING PROPELLER SHAFT AND BALANCE ARMS IN POSITION

which enables the gears of individual engines to take up their particular running positions.

Radial Engines.—" Bristol " engines use a reduction gear known as the bevel epicyclic type (Fig. 71), which consists of two opposed bevel wheels, one fixed and one revolving, between which are mounted three bevel pinions. The bevel pinions are freely mounted upon equally spaced stub arms radiating from the propeller shaft, and upon rotation of the crankshaft bevel these arms, and therefore the propeller shaft, are caused to rotate at a reduced speed.

An important feature of the construction is the mounting of the bevel wheels upon spherical thrust rings by means of which they are permitted a slight amount of universal

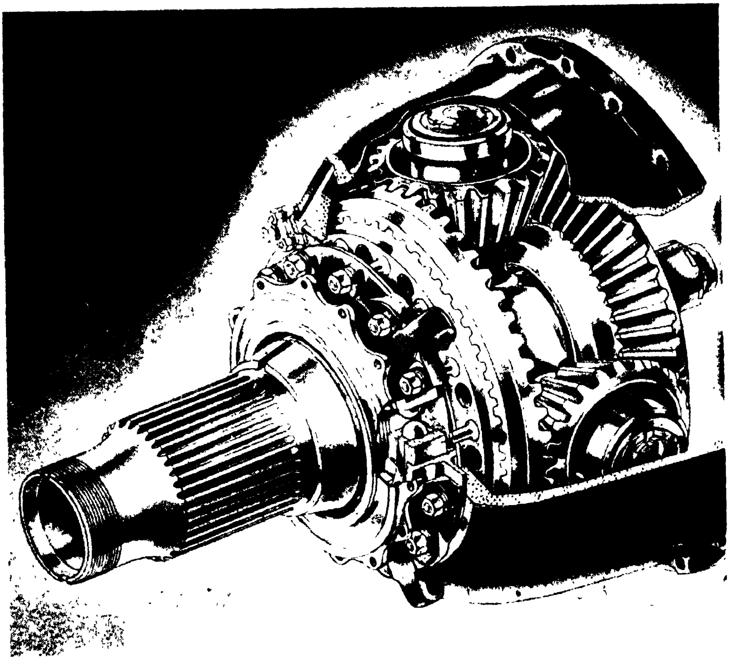


FIGURE 71 *By courtesy of The Bristol Aeroplane Co. Ltd.*

"BRISTOL" HERCULES BEVEL EPICYCLIC REDUCTION GEAR

movement. This movement provides a floating mounting for the wheels and ensures an even distribution of the load over the three bevel pinions.

The Armstrong Siddeley Cheetah XV engines are fitted with another type of epicyclic reduction gear (Fig. 75) comprising an internal gear, stationary sun gear and satellite gears. The internal gear is driven by the crankshaft and engages satellite gears mounted on bearings in a carrier secured to the propeller shaft. The satellite gears also engage the fixed sun gear carried on a floating mounting on the propeller shaft. In operation the satellite gears are constrained to move bodily around the sun gear and thus rotate the propeller shaft at a reduced speed to that of the fixed gear secured to the crankshaft. A similar arrangement is used on the Wright Cyclone

engine as shown in Fig. 72. In this assembly the inner stationary gear has a forward extension terminating in a flanged torque " arm," the unit being carried on ball bearings as illustrated. The purpose of this arrangement is to enable measurement of the torque reaction on the stationary gear.

As engine torque is proportional to brake mean effective pressure and brake horse power is proportional to this pressure and the engine r.p.m., the measurement of torque under actual operating conditions provides a most valuable check on performance and facilitates precision control of engine operation.

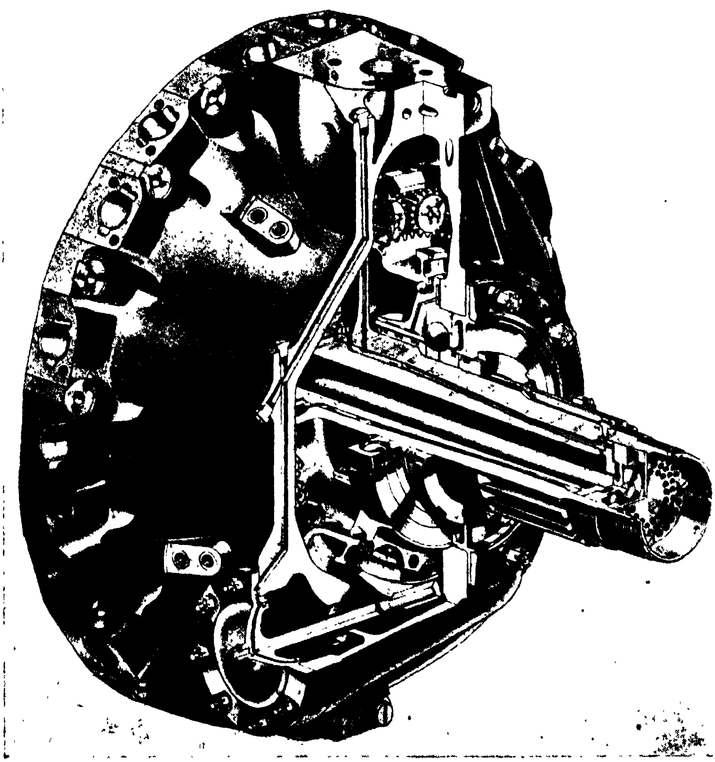
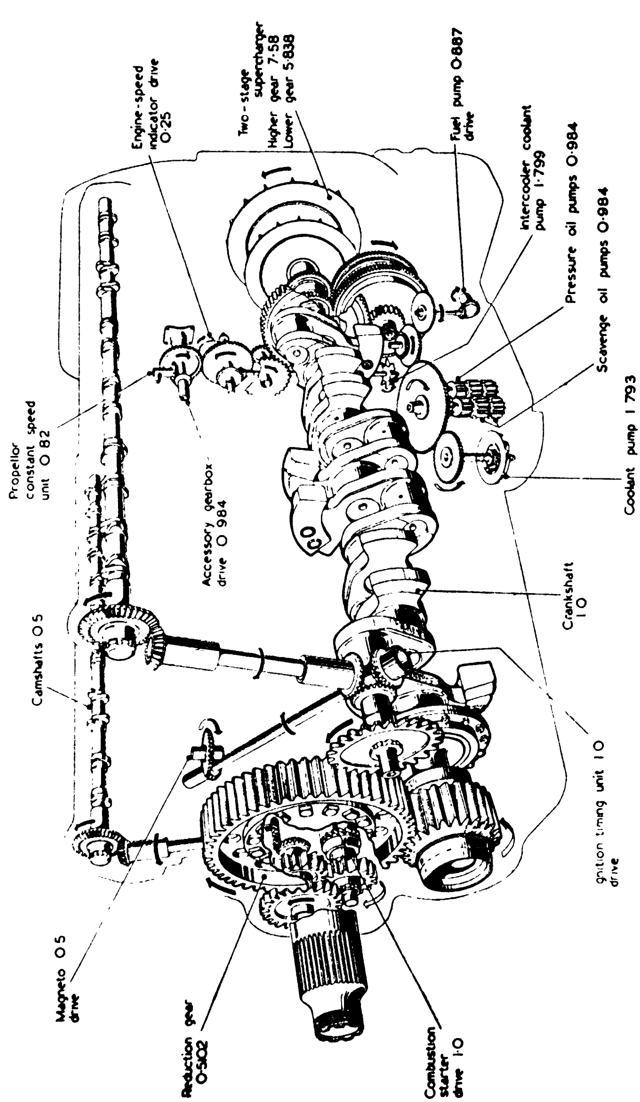


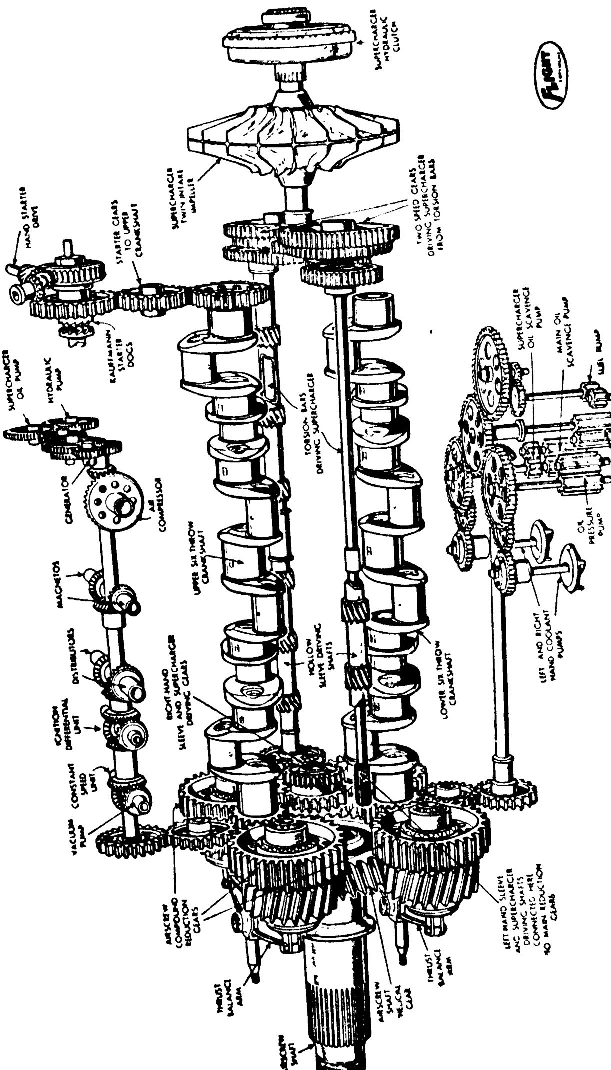
FIGURE 72 *By courtesy of Wright Aeronautical Corporation*

WRIGHT CYCLONE 9 HC ENGINE
TORQUE NOSE ASSEMBLY



By courtesy of Rolls-Royce Ltd.

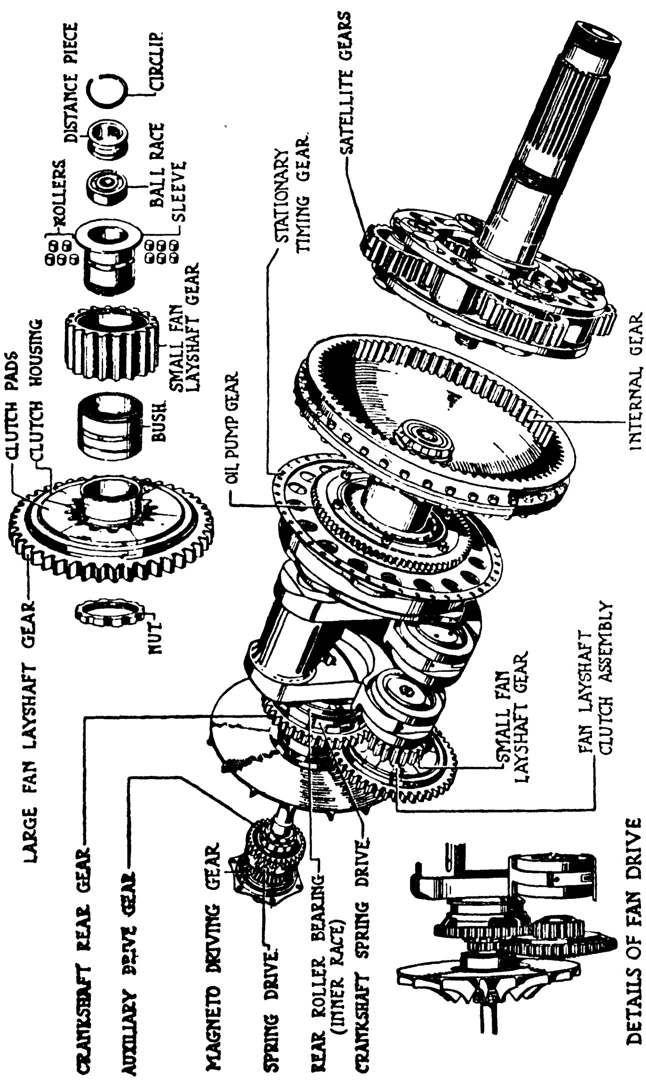
FIGURE 73
GRIFFON 65 TRANSMISSION DIAGRAM



By courtesy of Flight

FIGURE 74

SABRE II TRANSMISSION DIAGRAM



By courtesy of Armstrong Siddeley Motors Ltd.

FIGURE 75

CHEETAH XV TRANSMISSION DIAGRAM

In the Wright torque indicator, the outer end of the torque arm acts on a balancing valve, the force transmitted to this valve being balanced by oil pressure on the valve head. The pressure oil, displaced by a booster pump, is fed to the conical valve head by the internal passages shown. It is this oil pressure acting on the head of the valve which restrains the stationary gear from rotating.

When the engine is operating, the torque reaction of the gear causes the valve to move slightly to the left, and this produces an increase in the oil pressure acting on the valve head. The pressure increases until it is just sufficient to overcome the torque reaction and this causes the valve to move slightly right and to uncover metering ports in the sleeve in which the valve works. Oil escaping through these ports decreases the pressure until the torque reaction is again just sufficient to move the valve to the left. In practice an equilibrium condition of balanced oil flow is quickly reached and the valve takes up a position such that the amount of flow is just sufficient to maintain a pump pressure which just balances the torque reaction. This pressure is indicated on a gauge calibrated in brake mean effective pressure.

A torque indicator of another form is also fitted to some " Bristol " engines. In this type two torque-balancing pistons are used which arrangement eliminates the reaction at the central bearing.

The transmission layouts of the Griffon, Sabre and Cheetah engines are given in Figs. 73, 74 and 75, from which several of the details discussed may be noted.

CHAPTER IV

The Supercharger

As was previously briefly explained, the supercharger is a device whereby an extra weight of mixture is forced into the cylinders in order to increase the engine power output at ground level and at altitude. The power output of a normally aspirated engine, i.e., one without a supercharger, progressively decreases as altitude increases, and at approximately 18,000 ft. the full throttle power is only one-half that at sea level at the same r.p.m. (Fig. 76).

This falling off in power is brought about by the decrease in atmospheric pressure, which results in a less *weight* of air being passed to the engine, so that there is less available for

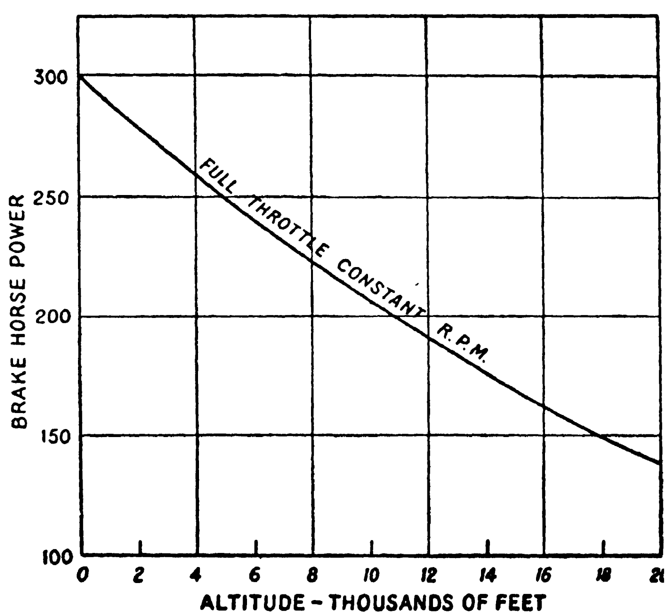


FIGURE 76

GRAPH ILLUSTRATING POWER DROP AT ALTITUDE - NORMALLY ASPIRATED ENGINE

combustion of the fuel (for complete combustion the theoretical weight ratio is 15 parts of air to 1 of petrol). The decreased weight of charge when combusted results in a decreased combustion pressure, and this effect is progressive up to the aircraft ceiling.

The primary object of the supercharger fitted to an aero engine is, therefore, to counteract this drop in power by delivering to the engine the same weight of air at altitude as would be required for normally aspirated full-throttle running at sea level. Above the maximum height at which this condition could be fulfilled the power would decrease similarly to that shown by Fig. 76.

The progress achieved in the development of supercharging as applied to "Bristol" engines is depicted graphically in Fig. 77.

There is no difficulty about obtaining the same weight of fuel at altitude, as with the float type carburettor it is not the weight but the *volume* of air per minute passing through the choke tube which determines the discharge of fuel from the jets.

With the later injection type carburettor, the fuel supply is automatically adjusted in accordance with the particular engine operating conditions.

Another important function of the supercharger is to increase ground-level power for the purpose of the aircraft take-off.

In order to achieve its object the supercharger draws in the fuel-air mixture and delivers it at a higher pressure to the induction system of the engine, so the device may be therefore considered as a type of compressor.

The supercharger fitted to British engines is known as a mechanically driven centrifugal type, and consists of an impeller or impellers (Figs. 83, 86), rotated at high speed through a gear train.

The impeller tip speed governs the compression ratio of the supercharger (i.e., delivery pressure to inlet pressure), and also the amount of power necessary to drive it. The tip speed depends on the impeller diameter and r.p.m., the former being fixed for a given engine while the latter can be varied—

either by varying the engine speed, or at a constant engine speed by means of two or three-speed gearing.

Due to the high speed of the impeller (about 20,000 r.p.m.) the mixture leaves the tips of the blades at high velocity, and consequently possesses greatly increased energy, which has to be converted into pressure energy for the purpose of providing the increased pressure in the induction pipes of the engine.

Referring to Fig. 83, a series of slightly curved vanes will be seen, these vanes surrounding the impeller a short distance away from the blade tips and diverging outwards. The divergent vanes, termed diffuser blades, form passages of increasing cross-sectional area which enable the mixture to decrease its velocity, this decrease being accompanied by a corresponding rise in pressure energy.

After leaving the vane ring the mixture is directed into an annular compartment which feeds the induction trunk or induction pipes to the individual cylinders.

As the speed of the impeller is high, it possesses considerable momentum, and its shaft would be subjected to exceedingly high stresses if violent fluctuations in engine speed were communicated directly to it. Also, due to the high gear ratio existing between the crankshaft and impeller shaft, even small changes in engine speed cause larger variations in impeller speed. For these reasons special drives are provided from the crankshaft to the impeller.

Spring Drive Gear.—On Bristol engines the impeller shaft is driven via a spring drive gear the construction of which is shown in Fig. 78. It consists of a central hub member which drives an outer gear rim through the medium of coil springs.

Due to this construction an angular displacement is possible between the hub and the gear rim, the fluctuations in engine speed being damped out by compression of the springs and are therefore not transmitted to the remaining gears of the drive.

Intermediate Gears (Fig. 83).—The spring drive gear engages with the pinions of the three two-speed clutches from which the final drive to the impeller shaft gear is taken. On single-speed gear drives the two-speed clutches are replaced by

friction clutch blocks through the medium of which the pinions drive the gear wheels so that, under certain circumstances, the pinions can revolve independently of the large gears.

When, for example, the throttle is opened and the engine quickly speeds up, these clutch blocks, under the action of centrifugal force, establish frictional contact with the internal surface of the gear rim and gradually take up the drive. If the throttle is suddenly closed or part closed, the pinions will slow down, thereby reducing the centrifugal force which actuates the clutches and the large gears, which are meshed directly with the impeller shaft gear, will " over-run," thereby safeguarding the impeller shaft from heavy loads.

In addition to relieving the drive and impeller shaft from the heavy loads caused by opening or closing the engine throttle, the construction of the intermediate gears allows the driving load to be equally distributed between the three.

Medium supercharged engines sometimes employ a single intermediate gear of this type, the Cheetah XV being an example. Reference to Fig. 75 will show the arrangement of the drives. The segmental clutch pads of the intermediate gear engage the pinion on their inner surfaces, while the outer establish frictional contact with the rim of the large gear. The Gipsy Twelve had another method of drive in which no spring gear or friction clutches were employed. The impeller gear train is driven by means of a long tubular shaft splined into the rear end of the airscrew shaft and driving the impeller gears at its other end, the torsional shocks being absorbed in " flexing " of the shaft.

This type of drive is also employed in the Napier Sabre, the torsion bar drives being taken via the reduction gears and forward ends of the sleeve drive shafts as shown in Fig. 74.

The Impeller.—The supercharger impeller now used is generally of the shrouded aluminium alloy type, a single or double shroud being employed according to the particular design. The former is typical of Rolls-Royce, Napier and de Havilland engines while the latter is a feature of present day " Bristol " engines. Earlier " Bristol " types such as the Pegasus and Mercury poppet-valve series utilized a steel

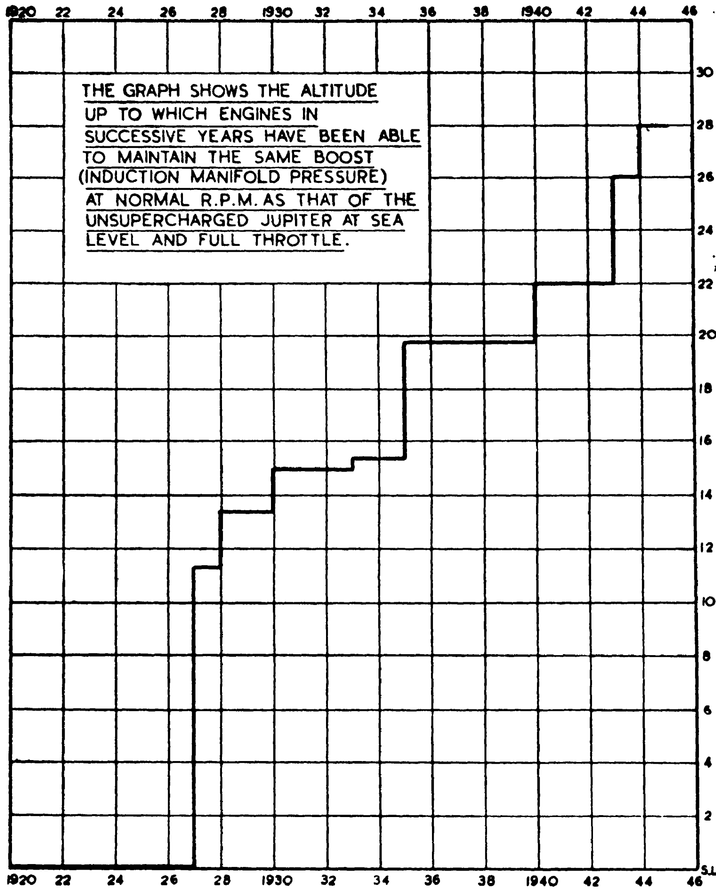


FIGURE 77 *By courtesy of The Bristol Aeroplane Co. Ltd.*

DEVELOPMENT OF SUPERCHARGING — "BRISTOL" AIR-COOLED RADIAL ENGINES

impeller having separate radial blades, i.e., unshrouded.

Double-Entry Supercharger.—A double-entry supercharger is one in which the mixture is fed to each side of a double impeller, the delivery from which is directed into a common induction chamber. A supercharger of this type was fitted to the earlier series of Napier Sabre engines as shown in Fig. 74, but this is now replaced by a single-sided impeller of increased capacity.

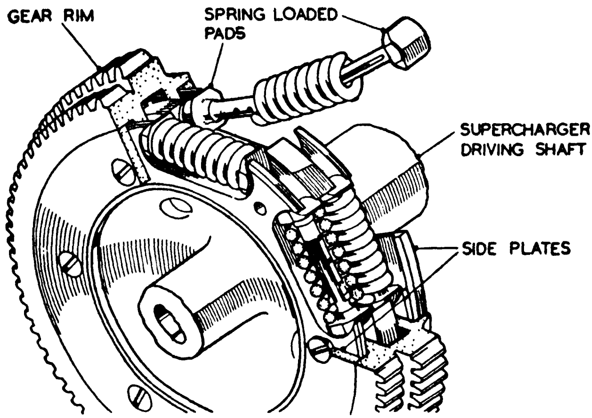


FIGURE 78 *By courtesy of The Bristol Aeroplane Co. Ltd.*

"BRISTOL" SPRING-DRIVE GEARS

LIMITATIONS OF SINGLE-SPEED SUPERCHARGER

The supercharger which is driven at one fixed gear ratio from the engine crankshaft is suitable for providing maximum take-off power and satisfactory climbing and cruising power up to an altitude of about 10,000 ft. This limit is set not by operating difficulties at the altitude but by the effect at sea level and low altitudes due to the high speed of the blower. A combination of maximum take-off power and maximum power at great heights is not a characteristic of the single-gear ratio blower. This is due to the fact that at sea level and low altitudes the engine speed may not differ greatly from that at high altitudes, consequently the blower speed is very high and its power absorption large under conditions when it is not required to deliver much pressure.

If, for example, a particular engine has a rated altitude of 10,000 ft., it means that at this altitude its supercharger is just able to maintain the rated power of the engine at full throttle opening and normal r.p.m. At all intermediate altitudes from sea level it will not be advisable to fully open the carburettor throttle, otherwise an excessive pressure will be obtained in the induction system, causing too high a power output with consequent engine damage. At sea level, therefore,

the supercharger has to be greatly throttled on its inlet side to prevent this excess pressure, the throttling being accomplished by the carburettor throttle which governs the intake to the supercharger. Unfortunately, due to the high speed of rotation, the power required to drive the supercharger is not reduced, thus, although the potential capacity of the supercharger cannot be utilized considerable power is required to drive it.

[As an indication of the power absorption, the supercharger of the Hercules XVI in the low gear ratio (two-speed drive), requires 205 b.h.p. to drive it for take-off at 2,800 r.p.m. (engine), and $8\frac{1}{4}$ lbs. per sq. in. boost pressure, $(8.25+14.7=22.75$ lbs. per sq. in. absolute).]

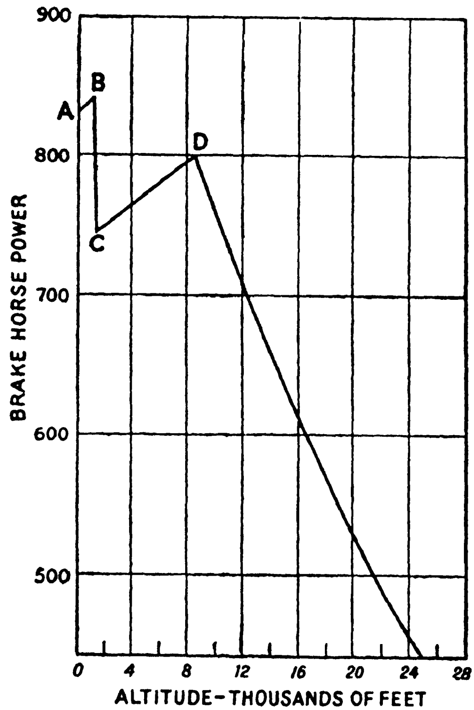


FIGURE 79

GRAPH ILLUSTRATING ENGINE PERFORMANCE AT TAKE-OFF AND AT ALTITUDE WITH SINGLE-SPEED SUPERCHARGER

Another factor is the temperature rise of the mixture undergoing compression in the blower, which reduces the density of the charge, thereby decreasing the nett weight delivered.

Both influences result in a reduced power output, which reduction increases with the speed of the blower ; consequently, although a high speed is necessary to maintain a given induction pipe pressure at high altitudes, it is detrimental to sea-level power.

It is for this reason that single-speed superchargers are made having either low, medium or high gear ratios. The low and medium type, owing to their slower speed of operation, absorb far less power at sea level and the engine therefore has available a higher nett power for take-off.

As the carburettor throttle will be more open in order to produce the necessary induction pipe pressure at the lower speed, the rated altitude (full-throttle running) will be lower.

In order to obtain high take-off power with high power at altitude, engines fitted with high gear ratio drives to the supercharger are nowadays made structurally strong enough to withstand higher degrees of supercharge at ground level than those used during normal flight. The higher delivery pressure is used only for a limited period or in an emergency.

A graph representing the powers available for take-off and at altitude for the single-speed high gear ratio type of supercharger is given in Fig. 79. When the aircraft is safely airborne the initial high degree of supercharge, or " boost " as it is commonly termed, is reduced, and there is a consequent drop in power from B to C.

From C to D the engine is operated at a normal boost, which is maintained constant by progressive opening of the throttle as altitude increases. At D the rated altitude is reached, the engine then operating at full throttle. From D the power will fall in a similar manner as that experienced with a normally aspirated engine from sea level.

The reason for the rise in power from A to B and from C to D while the engine is operating at a constant induction pipe pressure and constant r.p.m. is because the engine is ejecting

the exhaust against the decreasing atmospheric pressure and in consequence a less weight of exhaust gas remains in the cylinders prior to induction. Also the decreasing atmospheric temperature brings about an increase in density of the charge.

In Fig. 80 a similar graph is shown for the medium supercharged engine. The power drop from A to B after take-off is when the throttle is at a constant setting (often full throttle) at the high boost available, so that as altitude increases the boost decreases and the fall in power is analogous to that experienced on a normally aspirated engine. When take-off is at constant boost there will be a power rise from sea level to B as in Fig. 79. After the aircraft is safely airborne the throttle opening is reduced to give the normal operating

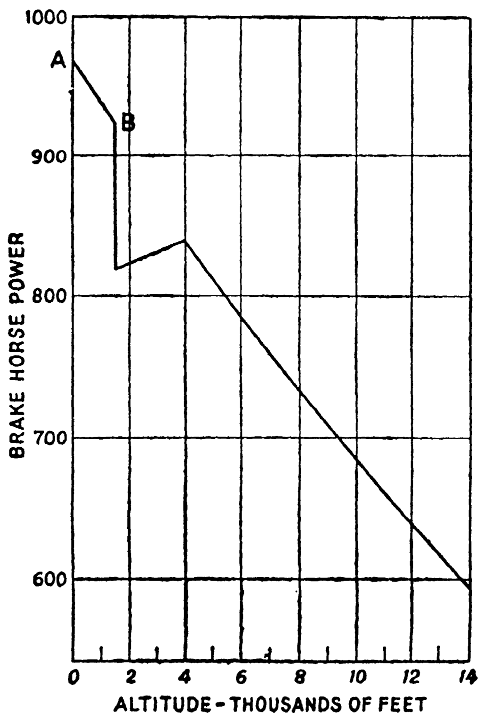


FIGURE 80
ENGINE PERFORMANCE AT TAKE-OFF AND AT ALTITUDE WITH MEDIUM SUPERCHARGE

boost, and from B onwards the conditions are similar to those of Fig 79, only that due to the lower r.p.m. of the supercharger the full throttle height for a given boost is lower.

TWO-SPEED SUPERCHARGER

In order to combine the high power available for take-off of the medium supercharged engine and the maximum power at high altitudes characteristic of the fully supercharged type, two-speed drives to the supercharger have been developed, and a typical performance curve is illustrated in Fig. 81. Take-off is made with an initial high degree of boost using the lower gear ratio drive to the supercharger. On reducing

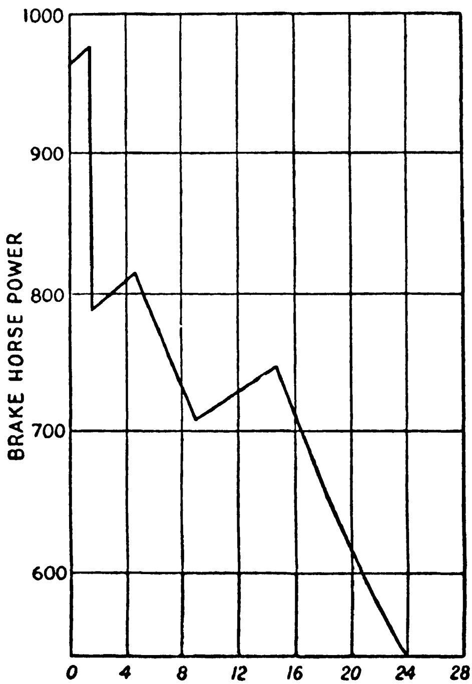


FIGURE 81

ENGINE PERFORMANCE AT TAKE-OFF AND AT ALTITUDE WITH TWO-SPEED SUPERCHARGER

to normal boost there is the usual power drop followed by a rise in power with altitude to the first rated altitude. Continued increase in altitude with full throttle running results in a falling off in boost and power until the gear change is effected, so increasing the r.p.m. of the supercharger. This results in an increased boost, an automatic control maintaining the normal value by partial closing of the throttle. The engine then commences to operate again at constant boost, and there is the rise in power until the second rated

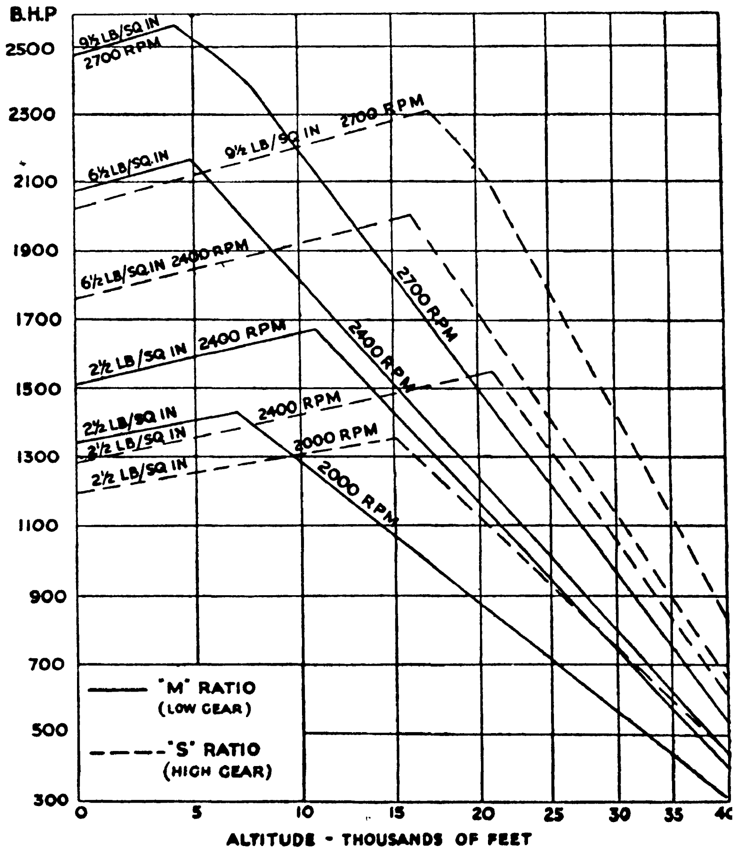


FIGURE 82

REPRESENTATIVE PERFORMANCE IN 'M' AND 'S' GEAR DRIVES

altitude, from which point power again falls. Engines fitted with two-speed superchargers are consequently rated at two altitudes, the first being the power available at full throttle rated boost and climbing r.p.m. with the low gear ratio drive in operation and the second for the high gear drive.

It should be realized that an infinitely variable gear drive to the supercharger would give a better engine performance, as in this case a speed could always be chosen which would allow the desired boost pressure to be obtained at *full* throttle. With fixed gear ratios it is necessary to restrict the throttle opening up to the rated altitude as the supercharger speed is too high and capable of producing excessive pressure for full throttle running. Power is thus wasted in driving it at the unnecessary high speed and then throttling it to limit its capacity.

Mechanical and weight complications have prohibited the use of infinitely variable drives and recourse has to be made to certain fixed speeds.

It is very necessary to employ the low gear ratio at sea level and low altitudes, as the power loss due to high gear operation at the same boost and r.p.m. is considerably in excess of that experienced in the low gear. As the difference at sea level is given as 260 b.h.p. for the Hercules XVI engine (at 8¼ lb./sq. in. boost and 2,800 r.p.m.), and 460 b.h.p. for the Centaurus 57, 58, 59 engines (at 9½ lb./sq. in. and 2,700 r.p.m.), it will be evident what regard must be paid to the choice of supercharger gear.

The total power loss of 260 b.h.p. given above is divided between (a) 85 b.h.p. increased power absorption in driving the supercharger in the higher gear (b) 175 b.h.p. loss consequent upon the increased temperature rise across the impeller which results in a lesser weight of mixture per unit volume.

In addition to the altitude power at rated conditions, i.e., climbing boost and r.p.m., engine altitude performance graphs also show powers available at other boost pressures and r.p.m. The full throttle height depends upon both the boost and the r.p.m. and with a constant speed propeller the r.p.m. can be adjusted by the propeller control. At a constant r.p.m., the

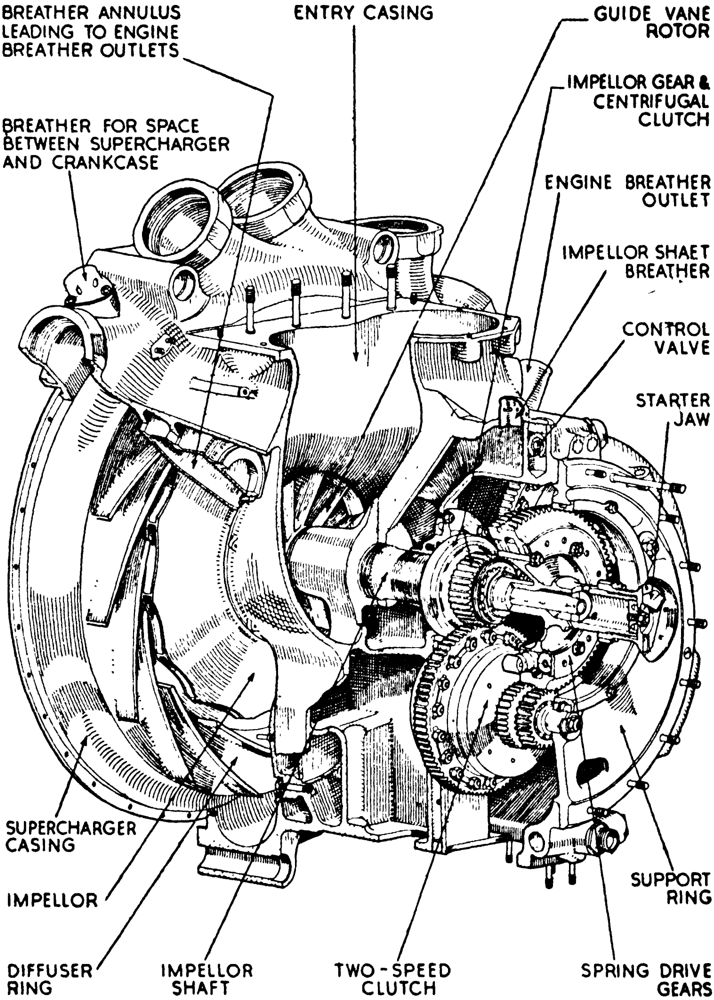


FIGURE 83 *By courtesy of The Bristol Aeroplane Co. Ltd.*

"BRISTOL" TWO-SPEED SUPERCHARGER DRIVE

lower the boost the greater is the full throttle height. At a constant boost, the higher the r.p.m. the greater also is the full throttle height.

If powers are given from sea level for both gear ratios—normally referred to as M (low gear), and S, then at the same

boost and r.p.m. the full throttle height will be greater in S gear although the power will be considerably less. This is due to the greater throttling necessary in S gear to limit the boost so that a greater height will be reached before the throttle is fully opened and the full capacity of the supercharger utilized.

Reference to Fig. 82 which gives representative performances, will assist in the understanding of these factors.

THREE-SPEED SUPERCHARGER

This new development of the two-speed drive is incorporated in a new series of Rolls-Royce Griffon engines of which Series 130 is typical, and is used in conjunction with a two-stage supercharger which will be discussed subsequently.

The three-speed drive is of course another step towards the ideal of "infinite variability," and with a supercharger of suitable capacity allows increased performance at all altitudes. Engagement of the highest gear drive after the full throttle height has been reached in the intermediate gear brings about a further increase in power and at increased altitude. At international rating the power is 1,280 b.h.p. at 31,500 ft. while under combat conditions, (five minute duration), the output is 2,050 b.h.p. at 21,000 ft.

A point of note in the design of this latest drive is, that the third speed and the increased diameter of the impellers to give a greater capacity, was incorporated without increase in diameter of the existing casings. The complete engine weighs 2,100 lb. with an output of 2,420 b.h.p. giving a weight/power ratio of 0.865 lb. per h.p.

The gear change is usually effected by hydraulic means utilizing the oil pressure of the engine lubrication system. In the "Bristol" two-speed supercharger (Fig. 83) the spring drive is formed with two separate but adjacent gears which are always in mesh with the two corresponding gears on the intermediate gear pinions. The intermediate gears incorporate clutches by means of which either of the two pinion gears is locked to its large gear, hydraulic operation of the clutch effecting the gear change.

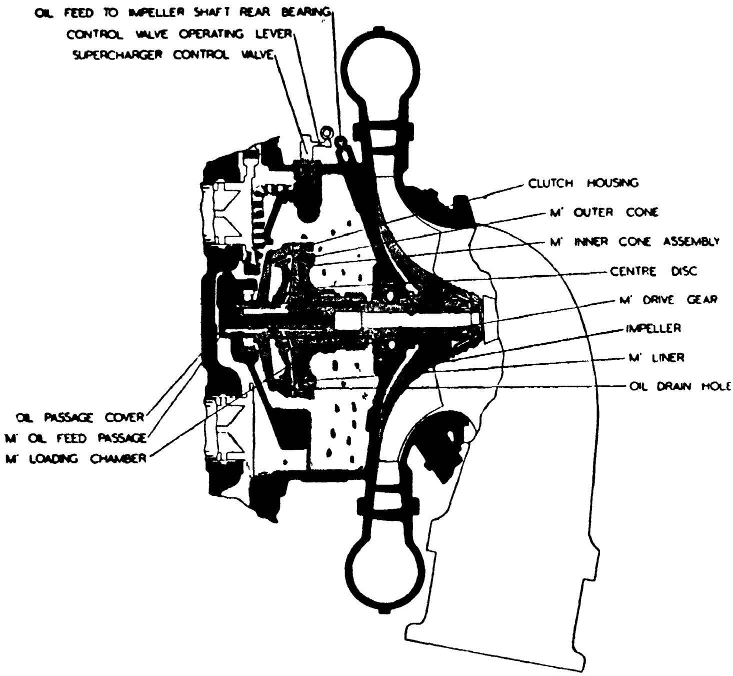
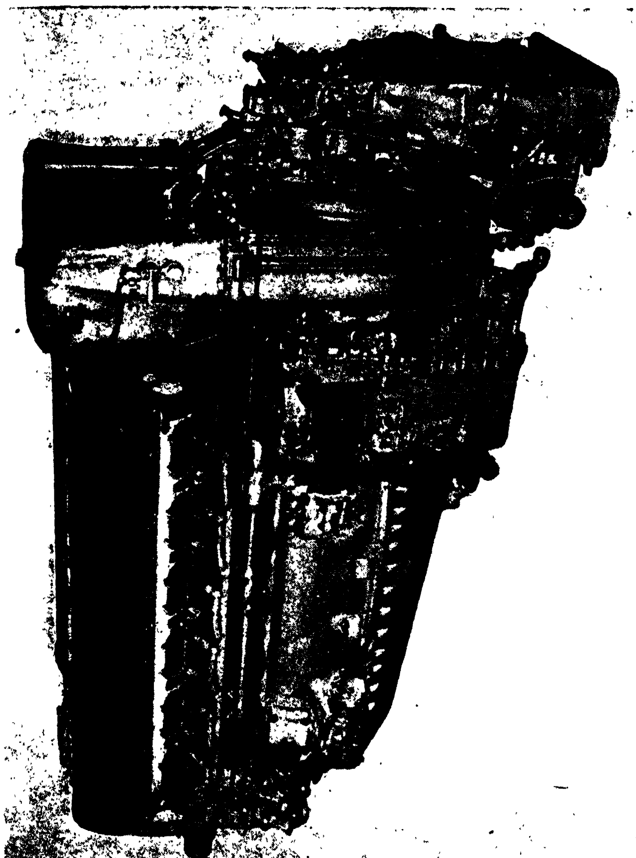


FIGURE 84 *By courtesy of D. Napier & Son Ltd.*

NAPIER SABRE V — OPERATION OF SUPERCHARGER TWO-SPEED GEAR DRIVE

The Napier Sabre has co-axial medium and high-gear shafts continuously driven by gearing from the two torsion rods. As shown in Fig. 84 each shaft terminates in a disc forming one member of a conical clutch assembly, and selective engagement to the clutch housing is effected by main oil pressure acting between a centre disc and the particular cone disc which has to be driven. The outer cone for the high speed shaft is formed in the clutch housing while that for the medium gear is carried by the centre disc as illustrated. The clutch housing forms the driving drum of the impeller shaft.

In the Rolls-Royce Griffon 65 (Fig. 86), the spring drive unit on the rear of the crankshaft drives the pinion of a hollow layshaft in which is contained a double-acting hydraulic



By courtesy of Rolls-Royce Ltd.

FIGURE 85

ROLLS-ROYCE GRIFFON 65 ENGINE WITH TWO-STAGE TWO-SPEED SUPERCHARGER

cylinder. Movement of this cylinder to the front or rear is effected by high pressure oil the circuit of which is determined by a separate two-position valve.

Mounted on the layshaft are the driving gears for medium and full supercharge and the friction clutches which couple the layshaft to whichever gear is selected. The clutches for the respective gears are mounted on either side of a driving member which carries six pivoted fly-weights whose position is determined by that of the hydraulic cylinder. When the cylinder has moved the inner ends of the weights to either side of the pivots, centrifugal force causes them to engage the clutch of the selected gear and thus drive the impeller shaft. The unclutched gear runs idle so that both are in constant mesh with the pinions on the impeller shaft.

In this arrangement the oil control piston valve is normally held in the medium supercharge position by means of a spring, an automatic change to full supercharge being made at the altitude where this is required. The change over is effected by an aneroid capsule which operates a switch to open a valve in the compressed air system of the aircraft. The air is led to one end of the oil control valve and acting on the piston lifts the valve thus reversing the oil distribution. This automatic change can be overridden by the pilot if necessary.

The assembly and drives of the two-speed supercharger as fitted to the Griffon 65 engine are illustrated in Fig. 86.

TWO-STAGE SUPERCHARGER

When high performance is required at altitudes in excess of those permitted by two or three-speed single-stage superchargers it is necessary to adopt another method of increasing the delivery pressure of the supercharger, and this is achieved by the addition of a second impeller which augments the delivery of the first the complete arrangement then being known as a two-stage supercharger.

The greatly reduced atmospheric pressure over about 16,000 ft. cannot be counteracted by the capacity of a single stage of compression by the centrifugal impeller at its limiting speed

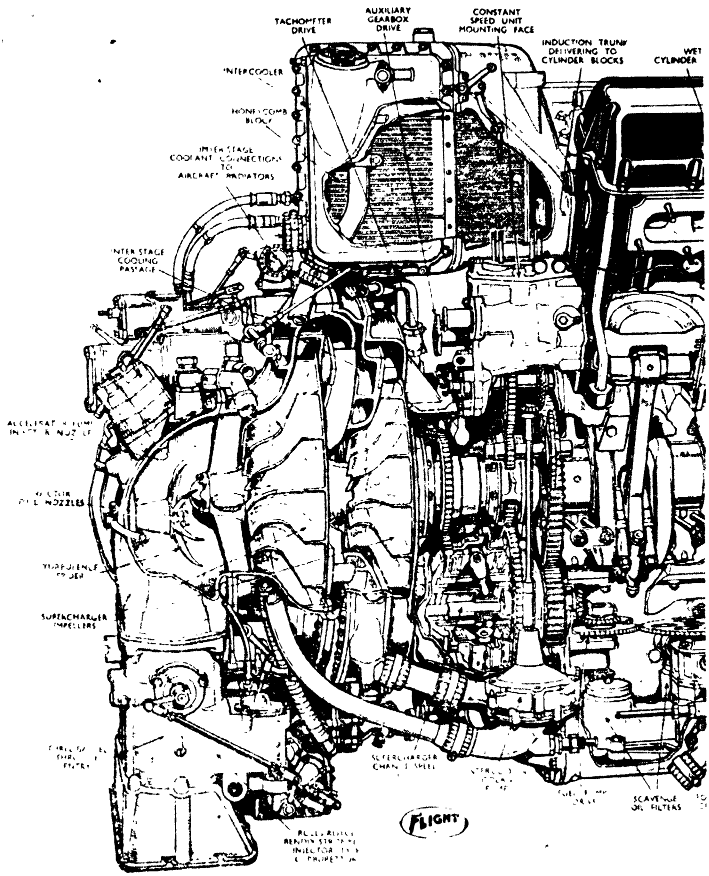


FIGURE 86 *By courtesy of* Flight

PART-SECTIONAL PERSPECTIVE VIEW OF ROLLS-ROYCE GRIFFON 65 TWO-STAGE TWO-SPEED SUPERCHARGER.

for efficient operation, so that the only means of maintaining the necessary induction pipe pressure is to add the second stage. The two-stage supercharger therefore consists of two single stages in cascade, the impellers being mounted on the same shaft and driven at the same speed.

The compression of the air or mixture passing through the superchargers is accompanied by a considerable increase in temperature which, by decreasing the density, would effectively lower the weight of charge per minute delivered to the cylinders unless intercoolers were fitted. Intercoolers are, therefore, an essential addition if the full benefit of the two-stage supercharger is to be derived.

The cooler is somewhat similar in construction to a radiator and is most easily fitted between the second stage delivery and the induction manifold as illustrated in Figs. 85 and 86.

In addition to the main intercooler it will be noted that passages for coolant are formed between the two stages. This intermediate cooling increases the capacity of the second stage by increasing the density of the mixture delivered by the first.

The special "Bristol" Pegasus engine fitted with a two-stage supercharger for the height record (49,967 ft.) in 1936 had a rated altitude at maximum r.p.m. of 42,000 ft.

If the second stage supercharger is always in operation, then, in order to provide good take-off power, it becomes necessary to have a two-speed drive. The low-gear drive is engaged for take-off and operation at the lower altitudes so that there is the minimum power absorption in driving the superchargers.

For the maintenance of power at extreme altitudes therefore, the two-speed two-stage centrifugal supercharger has been developed, noteworthy examples being the Merlin 61 and Griffon 65 engines.

In these engines the two aluminium alloy shrouded impellers are attached to a common shaft, the larger impeller for the first stage of supercharging being at the rear.

The mixture supplied by the carburettor is drawn into the first stage, the delivery of which is passed into the volute casing of the second stage.

From the second stage the mixture is led to the intercooler which is mounted at the rear of the induction manifolds between the cylinder blocks.

The intercooler consists of a honeycomb type radiator, into which the mixture passes and through which the coolant

is circulated by an independent pump. On the Griffon 65, the coolant from an external radiator enters at the base of the main intercooler and, after passing from side to side of the honeycomb block, leaves at the top and is led via an air separator to a pipe which couples to the intake side of the independent pump. The pump delivers the coolant to the inter-stage passages from which it goes to the external radiator. This circulatory system is independent of the main engine cooling.

THE TURBO-SUPERCHARGER

When superchargers were first developed for the purpose of maintaining sea-level power output at altitude, it was natural that designers should endeavour to utilize the considerable energy possessed by the exhaust gases as a means of providing the drive. The exhaust gas energy, hitherto unavoidably wasted, was to be harnessed and made to do useful work. In this way the turbo or exhaust-driven supercharger came into existence.

The actual supercharger is of the centrifugal type as previously described, but it is driven by an exhaust gas turbine instead of a gear train. The exhaust gases are delivered to a casing and, passing through inclined passages which act as nozzles, are directed to the blades of a turbine wheel (Figs. 87a, 87b), which is thus rotated at high speed. After passing across the blades, the exhaust is then discharged to atmosphere.

The supercharger impeller is mounted on the turbine wheel rotor at the opposite end to the turbine, and therefore revolves at the same speed.

At first it might appear that this method of drive is simply an alternative to the mechanical gear drive and that the performance of the two superchargers will not differ greatly, but further consideration quickly indicates that the performances are fundamentally different.

The speed of the turbo-supercharger is dependent upon the pressure difference existing between the exhaust manifold and

By courtesy of The Bristol Aeroplane Co. Ltd.

FIGURE 87A

"BRISTOL" TURBO-SUPERCHARGER

(*left*) Volute casing (*centre*) Turbine wheel and casing (*right*) Nozzle box with exhaust entry

turbine casing and that of the atmosphere, the greater the difference the higher the speed. Therefore, if the impeller can maintain sea-level induction pipe pressure at altitude, the engine will continue to exhaust at its normal sea-level manifold pressure and sea-level power output will be maintained.

These conditions are automatically maintained because, due to the decreasing atmospheric pressure with altitude, the pressure difference across the turbine correspondingly increases, the supercharger impeller revolves at a higher speed, and is thus able to maintain sea-level boost. In other words, sea-level power output is automatically maintained up to any altitude at which a critical speed of the turbine wheel or impeller is reached, which is in the neighbourhood of 28,000 ft.

In addition, unlike the geared supercharger, which has to be run throttled below its rated height (see page 109) the turbo-supercharger can give full power from sea level to the rated height, i.e., the power output is constant and not of the nature as indicated in Fig. 79. The carburettor throttle can be set at the desired position and need not be constantly adjusted (either manually or automatically), as is necessary when climbing at a fixed boost with the geared supercharger.

No slipping clutch or spring drive mechanisms are necessary as the exhaust gases provide a smooth drive free from the shocks associated with mechanical drives when the throttle is rapidly adjusted. The turbine wheel also acts as a flame damper and silencer.

In view of these advantages it may be wondered why the geared supercharger has been greatly developed and (in Great Britain) the turbo-supercharger has not made the same progress.

The chief reason no doubt has been the difficulty in obtaining materials for the turbine wheel and casing, which must withstand continuously the high temperatures prevailing in the exhaust system. When it is remembered that the exhaust valves of an aero engine operate at a red heat (600-700 deg. C.) it can be more easily imagined what constructional difficulties are presented when a turbine wheel revolving, say, at 30,000

FIGURE 87B *By courtesy of The Bristol Aeroplane Co. Ltd.*

"BRISTOL" TURBO-SUPERCHARGER

Reverse views of details illustrated in Fig. 87A.

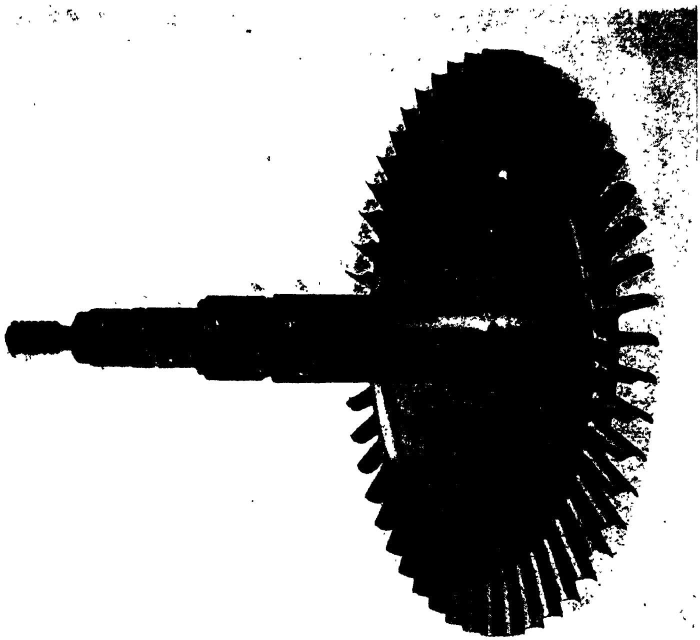


FIGURE 88 *By courtesy of The Bristol Aeroplane Co. Ltd.*
TURBINE WHEEL OF "BRISTOL" TURBO-SUPERCHARGER

r.p.m. has to operate at the same temperature. (The gas turbine does of course operate under similar temperature conditions and although the r.p.m. are less, the larger diameter of the turbine disc gives high tip speeds—about 1,200 ft. per sec. It should be realized that the success of modern gas turbines is greatly dependent on improved heat-resisting alloys).

Another factor is the back pressure in the exhaust system due to the obstruction caused by the turbine wheel. The exhaust piping must be pressure tight and has to withstand the higher temperatures consequent upon the obstruction of the turbine to free exit of gases. The exhaust back pressure also limits valve timing as regards overlap.

Due to the amount of heat evolved, it is necessary to position the turbine in the air-stream, and therefore, the compactness

of the geared type supercharger, particularly when fitted to radial engines, cannot be emulated.

Owing to the proximity of the supercharger to the turbine, it is necessary to fit an intercooler before the air or mixture is delivered to the cylinders, and this cooler is necessary in any case at the greater altitudes when the supercharger compression is highest.

Although the turbine is driven by the exhaust gases, the power loss due to the back pressure against which the pistons on exhaust stroke have to work is approximately the same as that absorbed by the geared supercharger.

This back pressure is operating equally at sea level, and will therefore cause a reduction in sea-level power output unless

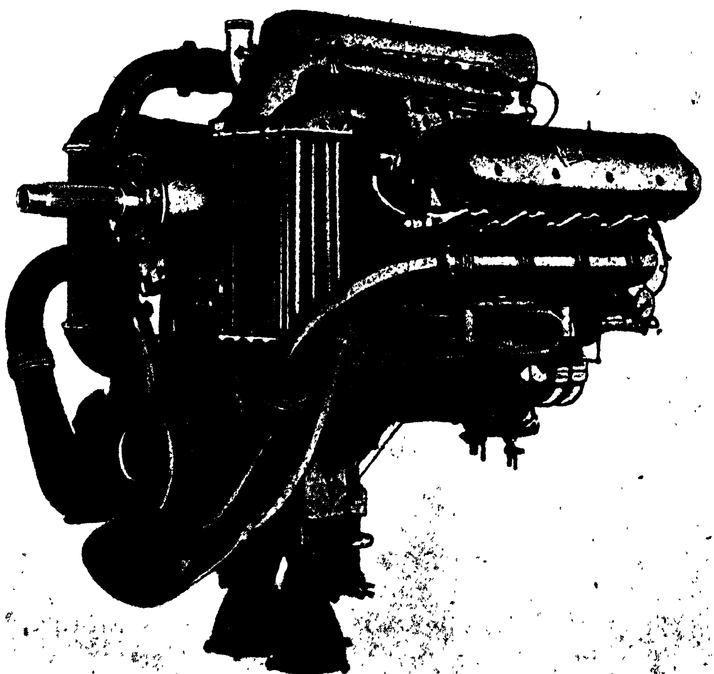


FIGURE 89 *By courtesy of D. Napier & Son Ltd.*

NAPIER LION ENGINE (1925) FITTED WITH TURBO-SUPERCHARGER

the gases are by-passed to atmosphere before the turbine. This can be done, as at sea level little or no delivery pressure is required from the supercharger.

An important modern condition which the turbo-supercharger cannot meet is that of ground boosting for take-off. As the high-geared supercharger is run throttled at take-off, an additional amount of throttle opening is accompanied by an increase in power output, and this higher power output is used for the take-off. The turbo-supercharger will be at full throttle at take-off, so that no additional boost can be available, although a combined geared and turbine supercharger would meet this case if either drive could be engaged or disengaged as required.

The above-mentioned considerations will explain why manufacturers' attention was centred on the development of the geared supercharger, especially as the added advantage of ground boosting was available.

However, for the maintenance of sea-level power at great altitude the turbo-supercharger has proved to be a satisfactory type, and the intense development carried out in America resulted in the sub-stratosphere flights of the American aircraft fitted with this type of supercharger (e.g., Boeing Fortress, Lockheed P38).

Both the geared and turbine-driven superchargers have their own particular applications, and this must be remembered when any comparison is made.

POWER BOOSTING

To permit very high power outputs without detonation for take-off, combat or emergency conditions, the system of methanol-water (methyl-alcohol and water), injection has been developed and is a feature of current engines. [Note: An alcohol and water injection system was devised and patented by H. M. Hobson (Aircraft and Motor Components, Ltd.) in 1920].

In normal engine operation for take-off at high boost, the mixture is enriched to about 10:1 air/fuel ratio in order to

provide ample fuel cooling and to suppress detonation. This rich mixture, as well as reducing the cylinder temperature also curtails the power, and the object of the methanol-water injection is to lower the charge temperature while retaining a mixture strength more nearly approaching that for maximum power.

The latent heat of evaporation of the injected mixture in lowering the charge temperature and thereby increasing its density allows a higher charge capacity, and in consequence even higher boosts can be permitted than those normally used for take-off. The power increase is therefore quite considerable.

For example, the " Bristol " Centaurus 57, 58 and 59 engines under normal operation have sea-level take-off powers in "M" supercharger gear of 2,475 b.h.p. at 2,700 r.p.m. and 9½ lb./sq. in. boost. With methanol-water injection at the same r.p.m. the boost is 11½ lb./sq. in. giving a power of 2,800 b.h.p.—an increase of 325 b.h.p. Similar increases are obtained on the Napier Sabre VII whose performance at take-off and combat conditions should be compared with those of the Sabre VA without the methanol-water injection.

The Series VA has a take-off power in "M" gear of 2,300 b.h.p. at 3,850 r.p.m. and 12 lb./sq. in. boost and a maximum combat sea-level take-off rating at the same r.p.m. of 2,550 b.h.p. and at 15 lb./sq. in boost. The Series VII with injection has a take-off and maximum combat sea level rating of 3,000 b.h.p. at 3,840 r.p.m. and 17 lb./sq. in. boost.

It should be noted that pure water injection will bring about an increase in power and although methanol is a fuel the main purpose of its addition is to prevent the water freezing at altitude, 60 per cent. methanol (by volume), giving such immunity to 40,000 ft.

For two-speed superchargers the methanol addition can be varied for each gear, and for the Sabre VII is 35 per cent. in low and 75 per cent in high gear respectively.

The equipment as fitted to the engine is automatic in action and incorporates safeguards which ensure that the higher boost cannot be used unless methanol-water is being supplied ;

that the methanol-water feed pump cannot function if engine conditions are not suitable for injection ; that when injection is in operation a weakening of the air-fuel mixture strength takes place ; that should the methanol-water tank run dry, the weakening jet and boost override controls are returned to normal.

A diagrammatic layout of such a system as applied to "Bristol" Centaurus engines is illustrated in Fig. 90.

To ground check the system it is permissible to give the engine a quick burst at take-off boost when the warning light will indicate correct functioning.

As an indication of the amount injected, the Napier Sabre VII at take-off conditions uses the mixture at the rate of 65 gall./hr.

Nitrous Oxide Injection.—Nitrous oxide retained in liquid form under pressure has also been used for power boosting above the rated altitude on German engines. In this system, the nitrous oxide supplies additional oxygen thus allowing an increase in charge capacity and also suppresses detonation due to the cooling effect. With an injection rate of 13.2 lb./min. a Daimler-Benz 603 E engine had an increase of 350 h.p. at 32,800 ft. When used on a Jumo 213 E engine at 19.8 lb./min. the increase was 418 h.p. at 44,300 ft.

BOOST CONTROL FOR MECHANICALLY DRIVEN SUPERCHARGERS

As the delivery pressure of a supercharger at sea level can be far in excess of the induction pipe pressure for which the engine is designed, it is most important that this pressure is controlled so as not to exceed the safe maximum value. (Power output is proportional to induction pipe pressure).

It has been mentioned previously that in order to maintain a safe operating pressure the inlet to the supercharger is throttled from sea level and at heights below the rated altitude. The particular delivery pressure or boost used is dependent upon the type of engine and the conditions under which it is operating, but for any given conditions it is important to maintain the boost at its proper value.

This condition would be almost impossible to realize if the throttle, which governs the inlet to the blower, was controlled directly by the pilot. Although there is a boost gauge to indicate the induction pipe pressure, it would need constant viewing, and for varying conditions of flight the pilot would need to constantly adjust the throttle. In fact, even if he had no other duties to perform, he could not efficiently control the degree of boost for varying flight conditions, and there would be great danger of damaging the engine due to excess power.

In view of this, all British supercharged aero engines are fitted with an automatic boost control by means of which the

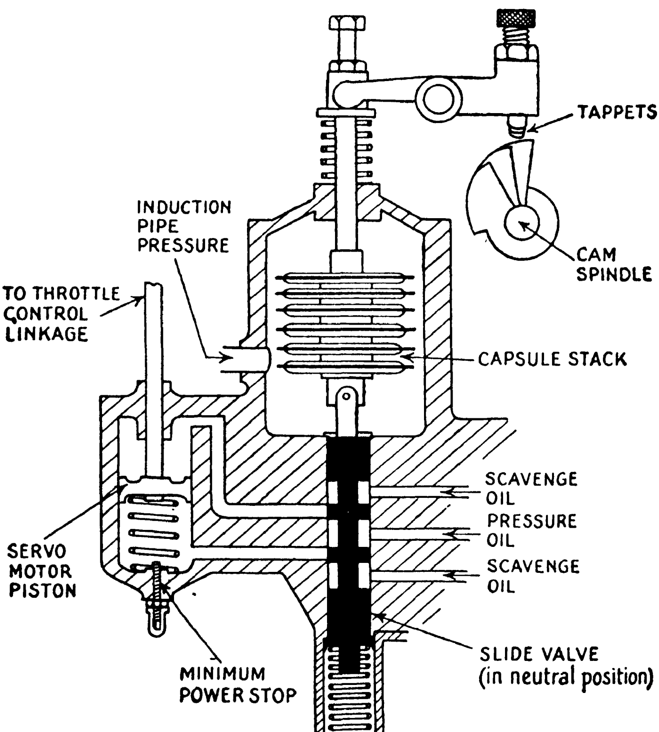


FIGURE 91

DIAGRAMMATIC ARRANGEMENT OF HOBSON 3-PHASE AUTOMATIC BOOST CONTROL

main portion of the throttle opening is governed. The pilot's cockpit throttle control is linked to this unit and not directly to the carburettor, so that during flight he is relieved of the vital necessity for precise adjustment of the boost, this function being automatically carried out by the special control.

A diagrammatic illustration of one type of unit—the Hobson automatic control—is illustrated in Fig. 91. The aneroid-type capsules are contained in a chamber which is open to the induction pipe pressure, so that a change in the pressure causes them to contract or dilate according to whether it rises above or falls below a fixed value.

Movement of the capsule stack is communicated to a slide valve which controls the passage of pressure oil to one side or the other of the piston of a servo motor, according to whether the capsules dilate or contract.

The cam spindle is partly rotated by movement of the pilot's throttle lever until the required boost value is selected by one of the three cams. This cam operates a tappet which in turn acts on the capsule spindle and fixes the datum from which the capsules will function.

If due to flight conditions an increase in boost pressure tends to take place, as for example, descending from an altitude at constant r.p.m. and pilot's throttle opening, the increasing atmospheric pressure will bring about an increase in the boost. This increase will also immediately affect the capsules, causing them to contract (Fig. 92), and therefore to raise the slide valve, which movement allows pressure oil to flow to the top of the servo piston and the same amount of oil to escape from underneath. The piston therefore moves down its cylinder and, being linked to the carburettor throttle, will commence to close it. Closing of the throttle reduces the supercharger delivery pressure, this reduction being also experienced by the capsule stack. When the induction pipe pressure has fallen to the fixed datum the slide valve moves to its neutral position and shuts off the oil, the piston stops, and maintains the throttle in the new position.

The reverse process takes place if the boost falls below the datum. In this manner the boost will be maintained at the

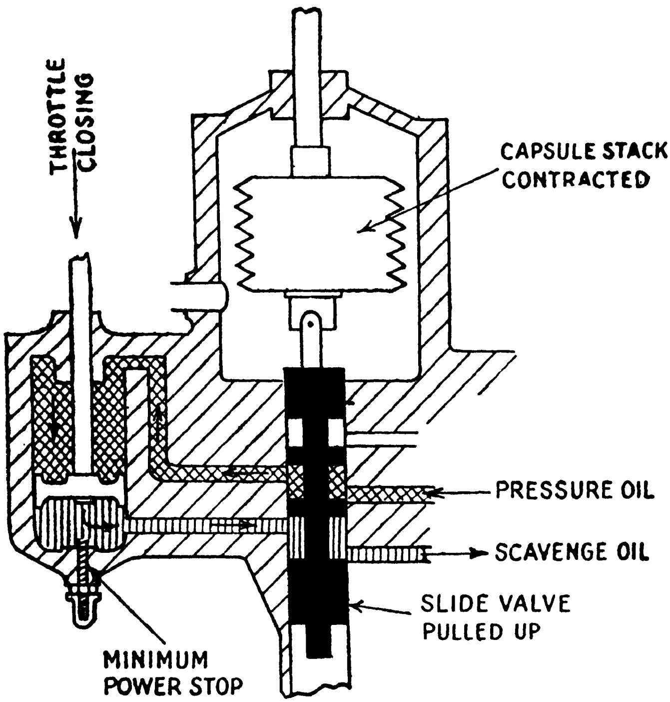


FIGURE 92
ACTION OF HOBSON AUTOMATIC BOOST CONTROL

desired value irrespective of the varying conditions experienced in flight.

The three cams mounted on the spindle which is moved by the pilot's throttle lever are for three degrees of boost, namely, take-off, rated and cruising boost.

The first is for the aircraft take-off when additional power is needed ; the second is for continuous climbing or level flight ; and the third is again lower for continuous cruising conditions, when fuel economy is more important than the power output.

On some engines there is also a higher degree of boost than that for normal take-off, which is brought into action by a separate control. The purpose of this extra high boost is to provide the maximum possible power output for take-off of

heavily laden aircraft or for use in combat or emergency. Special fuel has to be used on these occasions in order to prevent severe detonation or as previously stated a methanol-water injection system is employed.

As the automatic boost control is concerned with movement of the engine throttle, it is contained in a casing which is attached to the carburettor casting and the control linkage is often contained in an enclosed chamber. A carburettor fitted with an automatic boost and an automatic mixture control is referred to as a fully automatic carburettor, and a Hobson Master Control float carburettor of this type is illustrated in Figs. 96, 97.

CHAPTER V

The Carburettor

The carburettor for an aero engine is a very intricate mechanism, particularly so when it is of the type fitted to supercharged engines. It must provide a mixture of the correct fuel/air ratio for slow running, rapid acceleration, maximum power for take-off or all-out level flight, maximum power for continuous climbing or running, and economical consumption for cruising conditions. In addition it must counteract the effect of altitude on the mixture strength and incorporate safeguards to prevent excessive boost pressures or weak mixtures, both of which will cause damage to the engine.

In order to fulfil these requirements it is necessary to have special jets which will supply fuel at the correct periods when operational conditions demand and which will go out of action when the demand ceases. Moreover, the operation of these jets must not complicate the controls for the pilot, as often they need to be in action just at the time the pilot needs to concentrate all his attention on other matters.

As the action of these devices cannot be properly understood without some knowledge of the functioning of a carburettor and of the requirements which it has to meet, an explanation will be given.

FUNCTIONING OF THE FLOAT CARBURETTOR

The primary object of a carburettor is to supply a fuel/air mixture in the correct proportions and amounts for any required engine performance, and in order to do this there must be an accurately controlled fuel and air supply and means for thorough mixing of the two, as upon this depends the efficient combustion of the resulting charge supplied to the engine cylinders.

A float type carburettor has the following main parts: (1) a choke tube, (2) a float chamber, (3) a jet system, (4) a throttle valve, and a simple carburettor embodying these features is illustrated in Fig. 93.

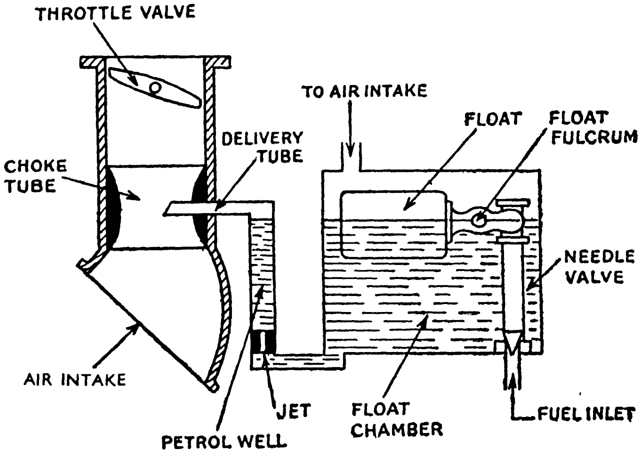


FIGURE 93
DIAGRAMMATIC ILLUSTRATION OF A SIMPLE CARBURETTOR

Air (i.e., oxygen) is necessary to support any form of combustion, and in the case of petrol 15 parts by weight of air are required to completely combust 1 part of petrol, i.e., 15 lb. of air will completely combust 1 lb. of petrol, and this ratio is a datum for the carburettor.

The air supply is drawn into the air intake due to the suction exerted by the pistons descending on induction stroke, and the object of the choke tube is to create a pressure drop which is utilized to draw fuel from the jet.

The main delivery tube for the fuel supply is therefore situated in this region of lower pressure (commonly referred to as a depression), although the actual main jet may be some distance away.

The object of the float chamber is to maintain a constant pressure or " head " of petrol irrespective of the amount discharged from the jets, and this is done by means of a needle

valve and float mechanism. When the chamber is full of petrol, the float, being pivoted on a spindle, pushes down the valve, so closing the fuel inlet. If the level tends to fall the float is lowered and the valve opens.

When the engine is not running the level of petrol in the jet delivery tube is the same as that in the float chamber, as they are connected in a U-tube manner.

With the throttle partly open, air is drawn through the choke tube and, due to the reduced pressure in the choke (that in the float chamber remaining unaffected), petrol is forced out of the delivery tube in the form of a spray and, mixing with the air, is carried to the engine cylinders.

As may be expected, this simple arrangement has many drawbacks, and its limitations are due to the inability of the system to adjust itself for the varying operational conditions previously mentioned.

Air-Bleed.—In the simple carburettor the neat fuel, issuing directly into the air-stream at the choke tube, is not sufficiently atomized for efficient combustion. To rectify this, an air supply, termed an air-bleed, is introduced into the fuel supply from the main jet prior to its delivery into the choke tube. This air has the effect of breaking up the fuel and supplying it in an atomized condition to the choke tube, where the atomization is completed, thereby securing more efficient combustion of the mixture.

The Diffuser.—Hobson carburettors employ a diffuser system which utilizes the air-bleed principle to provide atomized fuel. The diffuser (Fig. 94) consists of a brass tube through the walls of which are drilled a number of small holes, the tube being inserted into a petrol well fed from the float chamber via the main jet. When the engine is not running on the main jet the level of petrol in the well will be the same as that in the float chamber, but when the throttle is sufficiently open for the depression in the choke to draw fuel, petrol will be drawn from the well into the choke. As the engine speeds up, the level of petrol in the well will fall owing to the restricted feed of the main jet, and this causes the holes in the tube to become uncovered. The air entering the small nipple is drawn into

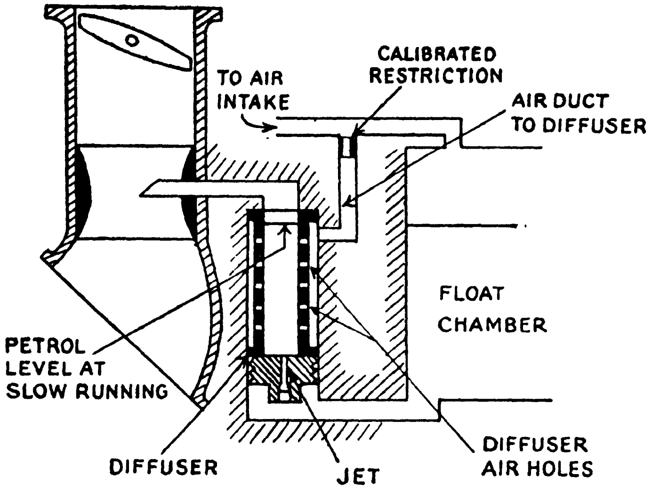
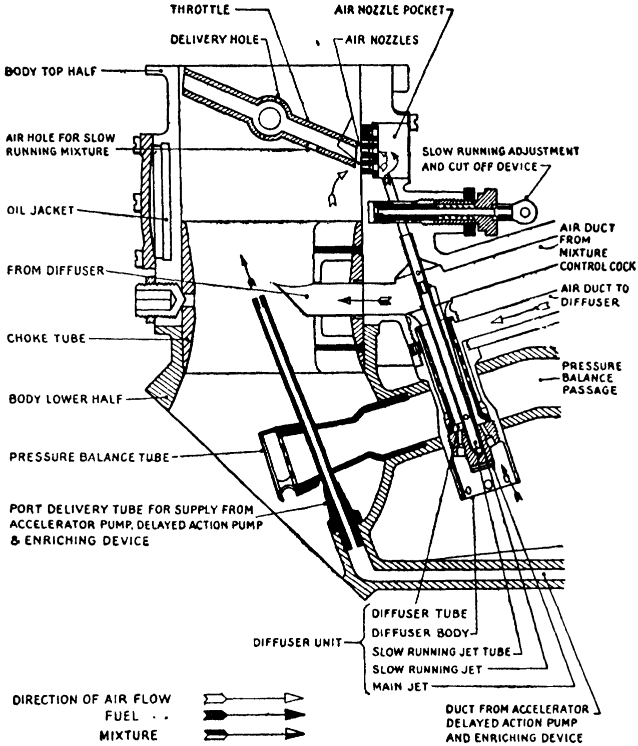


FIGURE 94
DIAGRAMMATIC ARRANGEMENT OF DIFFUSER AND AIR-BLEED

the annular space surrounding the diffuser tube, passes through holes, and, mixing with the fuel, is drawn into the choke. At full throttle the petrol level will have fallen to the bottom of the diffuser, allowing air to enter all the holes. As the amount of air drawn into the diffuser is progressively increased as the throttle opens, this also maintains the desired air/fuel ratio, which would decrease if no such compensation existed. [The richer mixture delivered by a simple jet (Fig. 93) as engine speed increases is due to the different flow characteristics of air and liquid].

Slow-Running.—When the engine is slow-running the throttle valve is almost closed and the amount of air passing through the choke is very small. In consequence the depression is negligible and no petrol will be drawn from the jet delivery tube.

At the " lip " of the throttle, however, there will be an appreciable depression, as the aperture there is very small, so that in an actual carburettor there is a separate slow-running system the delivery of which is drawn through an internal passage to the lip of the throttle. In some carburettors the throttle valve itself is made part of this system by being



From A.P. 1451C., by permission of the Controller, H.M. Stationery Office

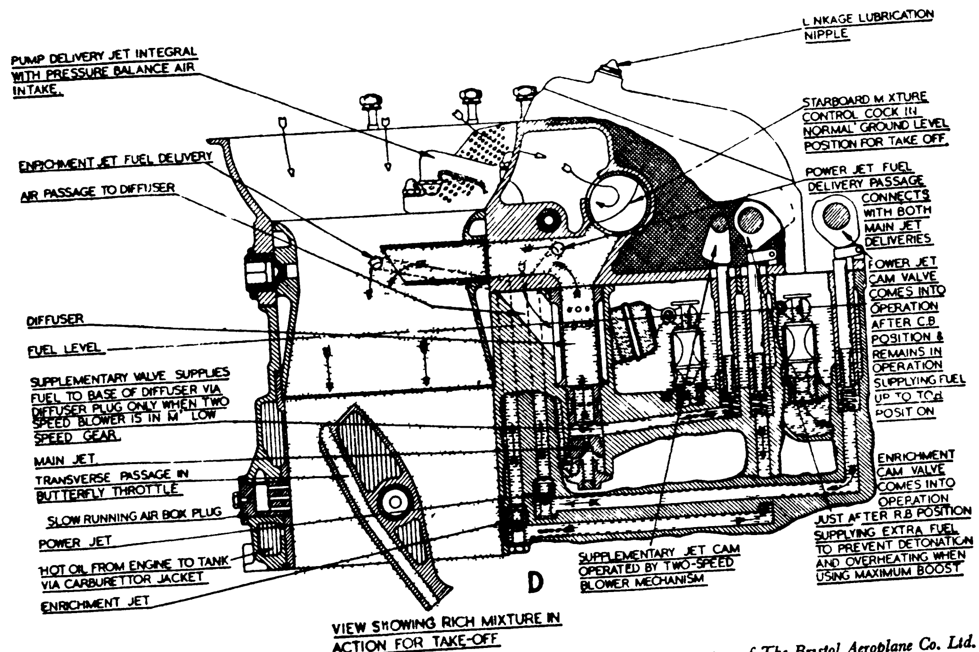
FIGURE 95

ARRANGEMENT OF SLOW-RUNNING SYSTEM

provided with a transverse passage into which mixture is fed and is distributed over the whole area of the induction pipe (Fig. 95).

Slow-Running Cut-Out.—When an engine is hot after flight, it does not always stop when the ignition is switched off, due to the hot cylinder igniting the mixture still being drawn through the slow-running system. In order to prevent this, a sliding valve (Fig. 95) is operated, which effectively blanks off the slow-running delivery passage from the jet, so that no mixture can be drawn into the induction system.

Power Jet.—When an aircraft is in flight and is cruising at part throttle opening an economical mixture strength is



By courtesy of The Bristol Aeroplane Co. Ltd.

FIGURE 96

HOBSON MASTER CONTROL CARBURETTOR A.I.T. 122M (HERCULES III ENGINE), SHOWING POWER, ENRICHMENT AND SUPPLEMENTARY JET DELIVERIES

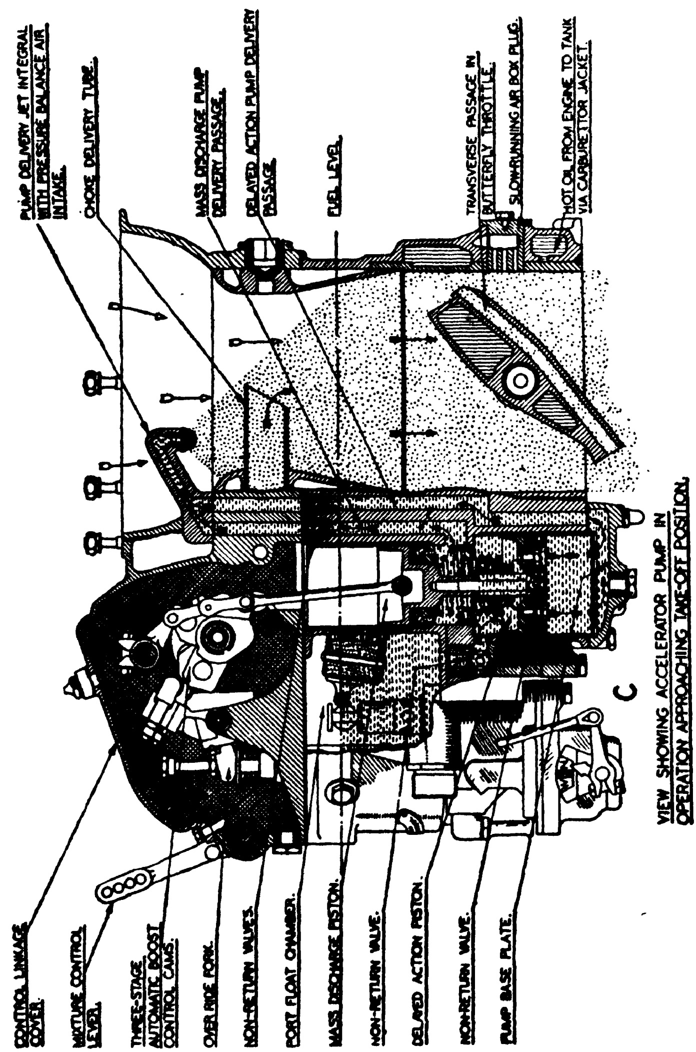


FIGURE 97

By courtesy of The Bristol Aeroplane Co. Ltd.

HOBSON A.I.T. 122M CARBURETTOR SHOWING ACCELERATOR PUMP IN OPERATION

desirable, i.e., one in which the air/fuel ratio is greater than 15 to 1. When, however, maximum power is desired, the throttle is advanced, and for power conditions an extra rich mixture (about 11 to 1) is essential.

The mixture strength cannot alter from economical to rich without some additional source of fuel supply, and the object of the power jet is to provide this extra supply.

The power jet (Fig. 96) is a jet which is supplied with petrol from the float chamber, but which only comes into operation under conditions when maximum power is required. (Note:—For supercharged engines this may be at a part throttle opening on the carburettor, as, for example, when taking-off at high boost). The neat petrol supplied by the jet is discharged either into the choke, into the air-bleed supply going to the diffuser, or into the diffuser delivery, and thus enriches the mixture.

Accelerator Pump.—In order to accelerate quickly a rich mixture is essential, so that when an engine is operating under cruising conditions on a weak mixture and it is desired to increase the r.p.m., some means must be provided whereby the mixture is richened, i.e., prior to the operation of the power jet. The accelerator pump is a device which injects petrol into the choke tube as the throttle is being advanced, thereby providing the necessary rich mixture for acceleration.

Delayed-Action Pump.—The accelerator pump gives a mass discharge of fuel into the choke tube in order to provide instantly the rich mixture necessary for acceleration to commence. To sustain the rich mixture for continued acceleration, another pump gives a timed discharge of fuel also into the choke tube, the discharge lasting about three seconds after that from the mass-discharge pump. In the actual carburettor the two pumps (Fig 97) are operated by the same downward stroke of a plunger interconnected with the throttle.

Enrichment Jet.—For take-off or all-out level flight, when high boost is delivered, a richer mixture than that given with the power jet in operation is required in order to prevent detonation and overheating. The enrichment jet (Fig 96)

delivers neat fuel into the choke tube for this purpose, and ceases delivery when the normal boost pressure is used after take-off.

Supplementary Jet.—This jet which was introduced on engines fitted with two-speed blowers is to enable a correct air/fuel ratio to be obtained at the two important flight conditions—maximum economy cruising in both low or " M " gear and in high or "S" gear.

An engine running at constant r.p.m., boost and intake conditions does not develop the same I.H.P. in high gear as in low gear due to the fact that with the former in operation the mixture charge is delivered at a much higher temperature. The air consumption is therefore lower.

As the air consumption is higher in low gear than in high, the air velocity through the fixed size chokes must also be higher, and this coupled with slightly different throttle angles changing slightly the pattern of air flow over the fuel discharge tubes, alters the relationship between air weight and pressure drop across the carburettor—the pressure drop is the factor controlling the amount of petrol metered.

It is to enable the carburettor to meter an accurate and constant air/fuel ratio over the range of air weight encountered under particular conditions that the supplementary jet is fitted. In the carburettor illustrated in Fig. 96, the delivery from this jet is made only when the blower is operating in low gear.

Power Bleed Jet.—On some supercharged engines, when there is a large cruising range of throttle opening, there is a tendency for the main jet delivery to weaken towards the end of the range just prior to operation of the power jet.

This tendency is counteracted by providing an extra jet which delivers neat fuel to augment the main jet supply during this particular portion of the range only.

Mixture Control for Altitude.—Due to the decrease in atmospheric pressure with increase in altitude, the weight of a given volume of air also decreases. The *volume* of air passing through the choke determines the depression there, and thus the fuel delivery from the jets, but it is the *weight* ratio of air to fuel that determines the mixture strength. As the weight of

fuel delivered by the jets remains unaltered, the mixture therefore becomes progressively rich as altitude increases, and combustion would be seriously affected if the air/fuel ratio were not corrected.

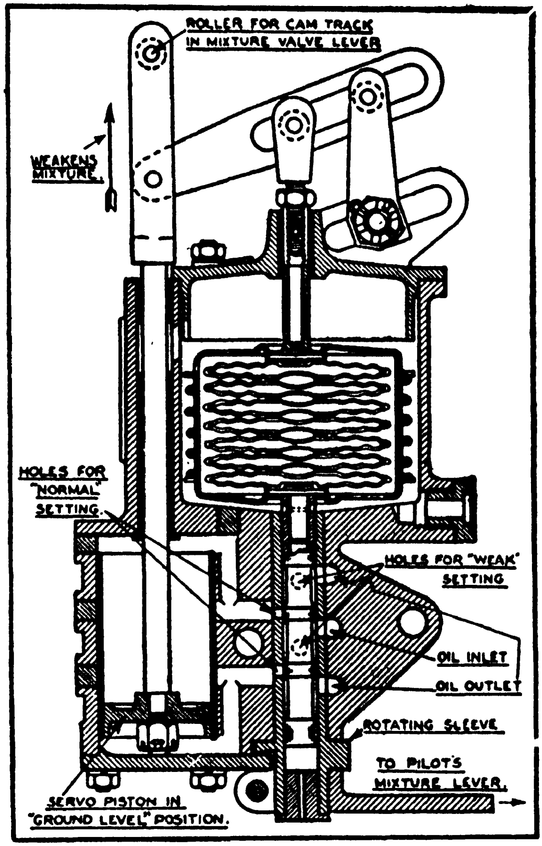
The carburettors of medium and high-powered supercharged engines incorporate an automatic control whereby the mixture strength is maintained constant at the desired setting, irrespective of changes in altitude. The control is also used to give weak mixtures for most economical cruising. In Hobson carburettors the automatic device controls the amount of air at atmospheric pressure which is allowed to be drawn to the head of the diffuser, this " air leak " reducing the depression existing at the diffuser, and thus less fuel is delivered to the choke as altitude increases.

Referring to Fig. 98, it will be noted that the capsule stack is attached to a sliding valve at one end, this valve controlling the oil flow to the piston of the servo motor in the same manner as that of the automatic boost control.

Unlike the boost control, however, movement of the servo piston is also communicated to the capsule stack via a sliding link and fork-ended spindle.

The action of the control is as follows. The capsule stack is influenced by atmospheric pressure, so that on the aircraft climbing the pressure decreases and the capsules dilate, thereby pushing down the sliding valve. The lands of the valve move away from the oil ports leading to the top and bottom of the servo motor cylinder, and pressure oil is fed to the head of the piston, thus pushing it up the cylinder. The upward movement of the piston rod is communicated in a lesser degree to the other end of the capsule stack, and the capsule cage being raised pulls the sliding valve upwards, so closing the oil ports and preventing further movement of the piston.

The forked end of the piston rod carries a roller which runs in a slot in a lever secured to the altitude mixture control valve of the carburettor, operation of which results in a weakening of the mixture, thus counteracting the richening which is brought about by altitude conditions.



By courtesy of H. M. Hobson (Aircraft & Motor) Components Ltd.

FIGURE 98

SECTION THROUGH HOBSON-PENN TWO-STAGE AUTOMATIC MIXTURE CONTROL FOR ALTITUDE

Atmosphere pressure is taken through an aperture in roof of capsule chamber

On earlier models the sliding valve is surrounded by a sleeve in which are drilled two pairs of oil ports, the pairs being at a different level. By partial rotation of the sleeve either pair of ports may be put into communication with the passages which lead to the servo-motor cylinder, and this forms the means by which the piston of the servo motor, and thus the

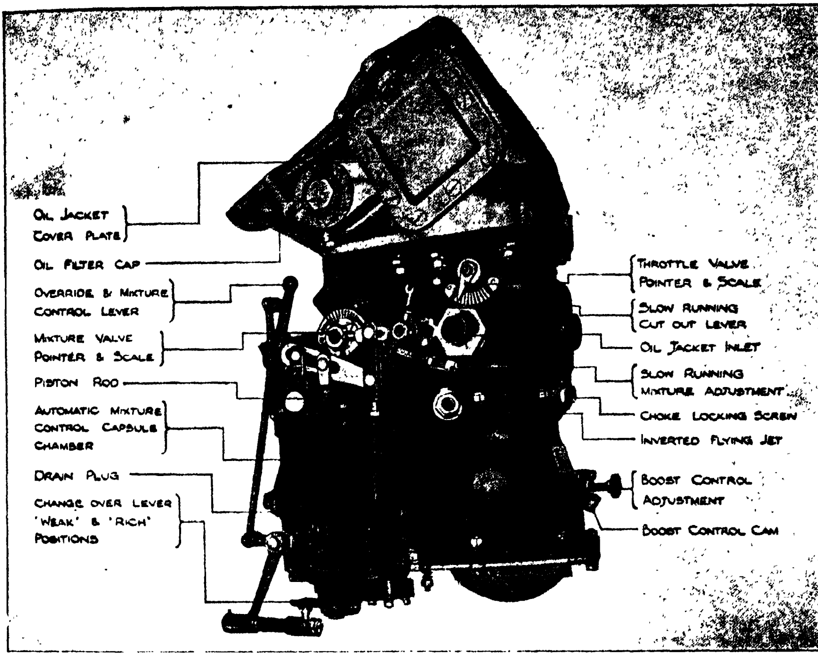


FIGURE 99 *By courtesy of Armstrong Siddeley Motors Ltd.*

HOBSON A.V. 70M CARBURETTOR (CHEETAH X ENGINE) SHOWING AUTOMATIC MIXTURE CONTROL

mixture control, is set at either " normal " (12 to 1 ratio) or, " weak automatic " (16 to 1 ratio) conditions, the weak automatic being used to secure fuel economy under cruising conditions.

As the piston will continue to move up its cylinder until the lands of the sliding valve cover the oil ports, it will be apparent that with the uppermost pair of ports in action the piston will travel higher in the cylinder, and thus open the mixture control valve a greater amount than when the lower pair are in action. The upper pair are therefore those for obtaining the " weak automatic " setting of the control.

The " automatic " refers to the automatic action of the control in maintaining the required mixture strength at varying altitude irrespective of whether the datum is a setting giving " weak " or " normal " mixture strengths.

The sleeve rotation is effected by means of the mixture control lever in the pilot's cockpit.

The location of the automatic mixture control unit on a Hobson A.V. 70M carburettor is shown in Fig. 99.

With this type of two lever control carburettor the " weak " setting is automatically tripped and reset to " normal," when the throttle lever is moved above cruising boost. This is necessary as with manifold pressures in excess of cruising boost, mixture enrichment is required and is provided by the " normal " setting together with other jets coming into action as previously described.

In later models this two position control is not fitted. The jet discharges in these carburettors are arranged to provide a 16:1 air/fuel ratio with the throttle lever in the cruising range and with increased boosts the necessary jets for enrichment are introduced. (It will be noted that in the earlier type the " weak " or 16:1 ratio position had to be manually selected).

The capsule chamber is also connected to the air intake as the " ramming " effect of high forward speed causes variations from atmospheric pressure.

Pressure Balance.—As the discharge of fuel from the jets is dependent upon the difference in pressure between the float chamber and the choke tube, it is important, for the preservation of constant mixture strength, that any changes in atmospheric pressure are communicated equally to both. If this is not so, then the depression in the choke tube would fluctuate, with consequent irregularity in the fuel discharged.

In aero-engine carburettors it is not satisfactory to put the float chamber in direct communication with the atmosphere as, due to flight conditions, the pressure at the air intake may not be the same as that in the vicinity of the float chamber. In consequence, the air space above the fuel in the float chamber is connected to the air intake by an internal passage, so that the pressure between the two is equalized or balanced.

Actual carburettors differ in respect of the location of the various valves, jets, etc., but the operating principles remain the same.

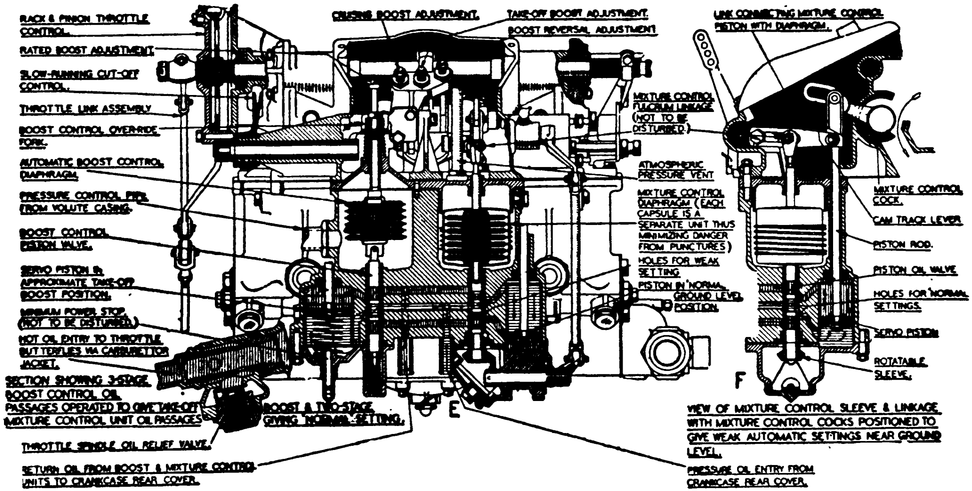


FIGURE 100 *By courtesy of The Bristol Aeroplane Co. Ltd.*]

HOBSON MASTER CONTROL CARBURETTOR A.I.T. 122M EMBODYING COMBINED AUTOMATIC MIXTURE AND BOOST CONTROL

A Hobson Master Control float type carburettor embodying an automatic mixture and automatic boost control is illustrated in Fig. 100.

Limitations of the Float Type Carburettor.—Although the float type carburettor has been developed over many years to a high state of perfection it has been always realized that this system of air/fuel metering had certain inherent disadvantages. The size of the choke tube, for example, is a compromise between the requirements of full throttle power where the least restriction to airflow is necessary, and those of part-throttle operation when the choke must be small enough to provide the required pressure drop with small airflows. With the best possible compromise the choke imposes a restriction at full throttle height thereby limiting both boost and power. In addition, the pressure drop across the choke is very sensitive to fluctuations at the air intake and although pressure balance minimizes the effect upon mixture strength, the shape of intake and degree of disturbance, do cause variations.

Another factor is the effect of aircraft manoeuvres, which due to the gravitational effect on the float and needle valve assemblies, cause similar variations in mixture strength. This particular failing has been counteracted by the development of an anti-G. float and needle gear.

Ice formation on the throttles is another factor which must be considered. In the normal float carburettor, the main fuel discharge into the airstream takes place before the throttle which is therefore favourably disposed for ice build-up consequent upon prevailing atmospheric conditions and the temperature drop due to atomisation. To avoid this, the intake air can be heated and a "hot" and "cold" intake system is normally fitted. It must be appreciated, however, that air pre-heating, due to density decrease, results in a lesser weight of air (per given volume), being passed to the engine, thereby altering the mixture strength.

It will be evident therefore, that in some respects the well established float carburettor can be considerably improved. This improvement has been realized and new features incorporated by the development of an entirely different system

of fuel flow control, one form of which is known as the Hobson-R.A.E. Master Control Injector. [Developed jointly by H. M. Hobson (Aircraft and Motor) Components Ltd., and the Royal Aircraft Establishment ; manufactured by the former]. Another type is the S.U. Injection Pump manufactured by the S.U. Carburetter Co. Ltd.

As modern piston engines incorporate one or other of these types the main features of each are described.

The Hobson-R.A.E. Master Control Injection Carburettor.—The outstanding feature of this new type is that the characteristic choke tube of the normal carburettor is no longer used, the fuel flow control being determined by the operating conditions of the engine itself.

The fuel requirements of an engine are in relation to its air weight consumption, this being proportional to engine r.p.m., boost pressure, induction temperature and exhaust back pressure, and these variables are made to govern the fuel discharge so as to maintain a given air/fuel ratio for a particular operating condition of the engine.

Referring to Fig. 101, fuel from an engine driven pump is delivered at constant pressure (normally 27 lb. per sq. in.), to a main metering valve the area of whose orifice is variable according to the boost pressure and induction temperature. As the flow through an orifice is dependent upon the pressure difference across it, this difference is arranged to vary with engine speed so that together with the correction applied for exhaust back pressure the fuel flow is metered according to all four variables detailed above. The metered fuel is then injected via spring loaded spray nozzles to any convenient position in the induction system.

The metering valve, which is coupled to the pilots throttle by linkage, slides in two sleeves so arranged that a small gap is left between them. The lower sleeve is fixed, while the upper is movable, so that the gap can be either increased or decreased, this movement being under the control of the induction temperature correction unit. This gap, in conjunction with a tapered slot in the metering valve, forms the variable orifice. It will be noted that the width of the orifice is

governed by the position of the slot in the gap, this being determined by the pilots throttle and a boost control capsule unit—i.e., the boost pressure, while the depth of slot is governed by the gap between the sleeves—this being determined by the temperature correction device. In other words, for a given gap between the sleeves, a definite boost pressure is associated with each orifice area and thus the amount of metered fuel.

Fuel Proportional to Engine R.P.M.—To meter the fuel in proportion to engine speed, the pressure difference across the variable orifice is controlled in the following manner.

The engine fuel pump incorporates within a separate compartment a small radial vane impeller driven at the same speed, the tips of which are supplied with fuel at the delivery pressure of the pump. The fuel flow to the eye of the impeller, consequent upon the reduced pressure there, is completed via jets and a compartment formed at the rear side of a diaphragm. The compartment at the other side of the diaphragm is supplied with fuel passing through the main metering valve. A pressure regulating valve which is attached to the diaphragm on this side controls the port opening through which fuel is delivered to the spray nozzles. On " Bristol " engines these are spring loaded to open at 12.5 lb. per sq. in.

The pressure difference across the impeller varies with the square of the r.p.m. so that with a tip pressure of 27 lb. per sq. in., that at the eye is progressively decreased as engine speed increases.

By reference to Fig. 101, it will be noted that the pressure across the main metering valve orifice will also be the same as that across the impeller. The inlet side of the orifice is at the constant pump pressure of 27 lb. per sq. in., while that of the outlet is determined by the pressure regulating valve and diaphragm. As the diaphragm will deflect until the pressure on each side is equalized—and that at the rear is impeller eye pressure—the orifice delivery side will also be at this pressure. Therefore, as the engine speed increases, the pressure difference across the impeller increases, thus lowering the pressure in the rear diaphragm chamber.

The diaphragm will move in this direction and the attached pressure regulating valve will be moved in the opening direction thereby allowing more fuel to flow to the spray nozzles. As this fuel flow increases, the pressure on the delivery side of the main metering orifice will also decrease, (due to the increased velocity of the fuel), but the diaphragm will move the regulating valve until the pressures in front and rear chambers are equalized.

In this manner the pressure drop across the metering orifice, and thus the fuel flow, is increased proportionately to engine speed.

At this stage the fuel flow has been considered in relation to boost pressure (varying area of orifice), and engine speed (varying pressure difference across orifice).

The two remaining variables, temperature and exhaust back pressure, have now to be related.

Temperature Correction.—At constant boost and r.p.m. the weight of air (or mixture) consumed by the engine is influenced by its temperature. Increase in temperature lowers the density (weight per unit volume), and thus the weight of air consumed. As the air/fuel ratio is determined by weight, any such alteration will affect the mixture strength unless some correction is applied. This variation in temperature is not only concerned with that occurring at the air intake but also after compression by the supercharger. With two-speed or three-speed gear ratios there is a considerable temperature variation at the supercharger delivery when changing gear at constant r.p.m. and boost due to the different compression ratios obtained. For this reason the temperature sensitive element used in the correction unit is situated in the engine induction manifold.

A mercury thermometer bulb in the induction manifold is coupled by a capillary to a mercury filled Bourdon tube, the other end of which is attached to a lever, pivoted on a ball bearing mounted fulcrum. The opposite end of this lever is forked to engage with the head of the movable sleeve in which the main metering valve works. This movable sleeve is spring loaded and urged upward against the lever fork.

If the induction temperature increases, the expansion of the mercury in the bulb is transmitted to the Bourdon tube which then tends to straighten. This movement is conveyed to the pivoted lever, the fork of which in turn depresses the spring loaded sleeve. Downward movement of this sleeve reduces the size of the main metering orifice as previously explained, the amount of reduction being in accordance with the desired relationship between temperature and fuel flow.

With decrease in induction temperature the sleeve is spring-urged upwards according to the amount of contraction of the mercury. Fuel flow is thus corrected for induction temperature variations.

Exhaust Back Pressure Correction.—The reduction of back pressure on the engine exhaust due to the decrease of atmospheric pressure with altitude, diminishes the weight of exhaust gas remaining in the cylinders. (The gas has to be forced out against the surrounding atmospheric pressure, thus the lower this pressure, the greater becomes the amount ejected). Therefore, at any given r.p.m. and boost, the lesser weight of exhaust gas remaining allows a proportional increase in the weight of air admitted on induction. It is this increase that makes a correction unit necessary in order to maintain a given mixture strength, i.e., air/fuel ratio. With decreasing exhaust back pressure additional fuel is required and vice-versa. Variations in back pressure also occur when engines are fitted with turbo-blowers and the correction unit also compensates for these conditions.

As indicated by Fig. 101, the unit consists of a capsule stack enclosed in a chamber and subject to either atmospheric or exhaust back pressure. The stack, being responsive to pressure variations, will raise or lower the needle valve attached to the underside. This valve works in a calibrated orifice through which fuel from the entry side of the main metering valve can pass to the delivery side.

Decrease in atmospheric pressure allows the capsule stack to expand thus lowering the needle valve in its orifice and permitting an increased fuel flow to the delivery side of the

main metering valve. The reverse takes place when atmospheric pressure increases as an aircraft descends from altitude.

An adjusting screw connected to the top of the capsule stack is initially set by the manufacturers to allow a specified fuel flow under ground level conditions.

In this manner the total fuel flow is made proportional to boost pressure, engine speed, induction temperature and exhaust back pressure.

Normal Mixture Jet.—This jet, shown in Fig. 101 is located between the main fuel supply from the pump and the rear diaphragm chamber and is fitted to provide adjustment of mixture strength.

The fuel flow from the rear chamber to the eye of the impeller is governed by a jet fitted at the inlet to the eye. If therefore, the size of the normal jet is increased, the pressure in the rear diaphragm chamber will increase, thus moving the diaphragm and pressure regulating valve in the closing direction and reducing the fuel flow to the spray nozzles. Larger jets therefore give weaker mixtures and vice-versa. In some units this jet is made adjustable by the incorporation of a needle valve, but the adjustment is for ease of initial setting on test and should not be disturbed subsquently.

Weak Mixture Jet.—This jet is fitted to injectors for "Bristol" Hercules 100 and Centaurus engines, its purpose being to give a weakening-off in mixture strength over the economical cruising range. As shown in Fig. 101, fuel at main pump pressure is permitted to pass through the calibrated jet when the rotary valve moves through a predetermined angle. Fuel from the jet passes to the rear diaphragm chamber thus increasing the pressure and causing the diaphragm with the regulating valve to move slightly in the closing direction, thereby lessening the fuel flow.

Slow Running Jet.—This jet as fitted to "Bristol" engine injectors is in operation for the first few degrees movement of the throttle layshaft and allows a flow of fuel to the front diaphragm chamber. The resulting increase in pressure causes the diaphragm and regulating valve to move in the opening direction thus allowing extra fuel to be delivered to

the engine. The jet is adjustable so that the desired mixture strength for smooth slow running can be obtained.

Accelerator Pump.—For rapid acceleration, this unit (Fig. 102), delivers a controlled amount of additional fuel to the spray nozzles. Linked to the pilots throttle is a small piston working in a cylinder, the space above the piston being supplied with fuel at main pump pressure. In communication with each end of the cylinder is a separate compartment divided by a flexible diaphragm which is spring-loaded against a ball valve. This valve, normally closed, prevents additional fuel from reaching the engine, except under conditions of acceleration. The small clearance of the piston in the cylinder allows fuel to reach the underside and via a port also the space underneath the diaphragm.

During slow-running, the piston is at the bottom of its stroke, but when the pilots throttle is advanced, it is raised, thereby lowering the pressure underneath, thus causing the diaphragm to be deflected downwards. This movement allows the spring-loaded ball to be unseated and fuel at main pressure is able to flow past into the duct to the spray nozzles.

The space left underneath the piston due to its upward travel is replaced by fuel from the upper side leaking past, the clearance being so regulated that the equalizing of pressure takes sufficient time to ensure good acceleration. When the pressure equalizes, the diaphragm will return and again seat the ball valve thus cutting off the additional fuel.

To allow the piston to move down freely when the pilot retracts his throttle, another spring-loaded non-return ball valve is fitted which permits fuel to flow freely from the lower to the upper side when displaced by the descending piston.

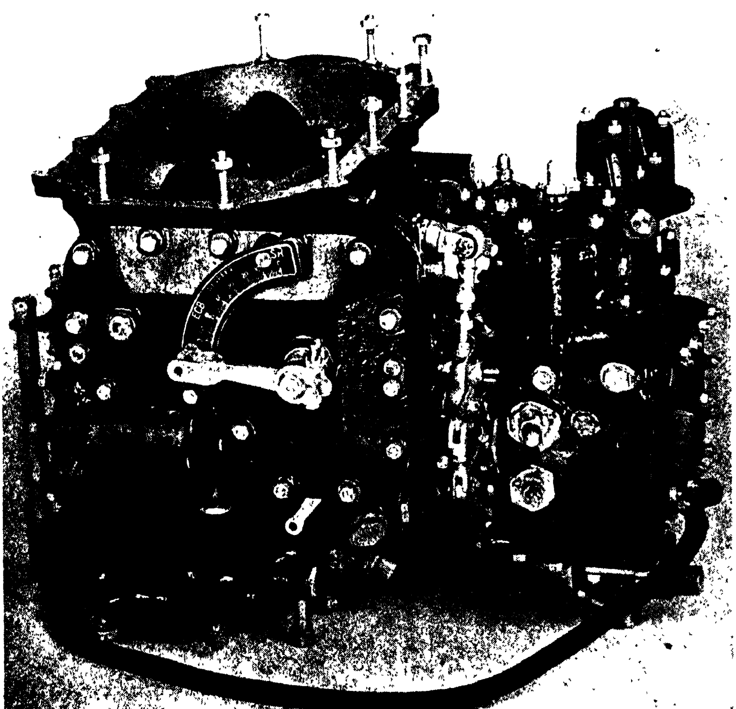
The actual quantity of additional fuel supplied by the accelerator unit is adjusted by means of a tapered needle valve fitted in the supply line from the unit to the spray nozzles. This valve is set for particular engine requirements, and when so set initially should not be disturbed.

Slow-Running Cut Out.—In this carburettor, the fuel cut-out to prevent a hot engine from firing when switched off, is a [illegible] valve which, when operated, closes the immediate passages

leading to the spray nozzles. It is operated by a lever and is spring-loaded in the open-position.

Vent Valve.—This valve shown in Fig. 102, is automatically operated to provide a vent for any air which might be introduced into the fuel pump, and for air or vapour present in the fuel system when priming preparatory to starting up the engine.

As air introduced into the fuel pump reduces its pumping capacity, and as the spray nozzles are set to blow off at 12½ lb. per sq. in. (" Bristol " engine), it would be difficult to expel the air and maintain the required fuel pressure if no provision was made for venting—which allows the air to be expelled



By courtesy of H. M. Hobson (Aircraft & Motors) Components Ltd.

FIGURE 103

PORT SIDE VIEW OF HOBSON R.A.E. INJECTOR TYPE B.I./B.H.5.

(See fig. 4 for starboard side view and attachment to engine)

back to the fuel tank, and for the period that this is being done, allows the pump to work at reduced pressure.

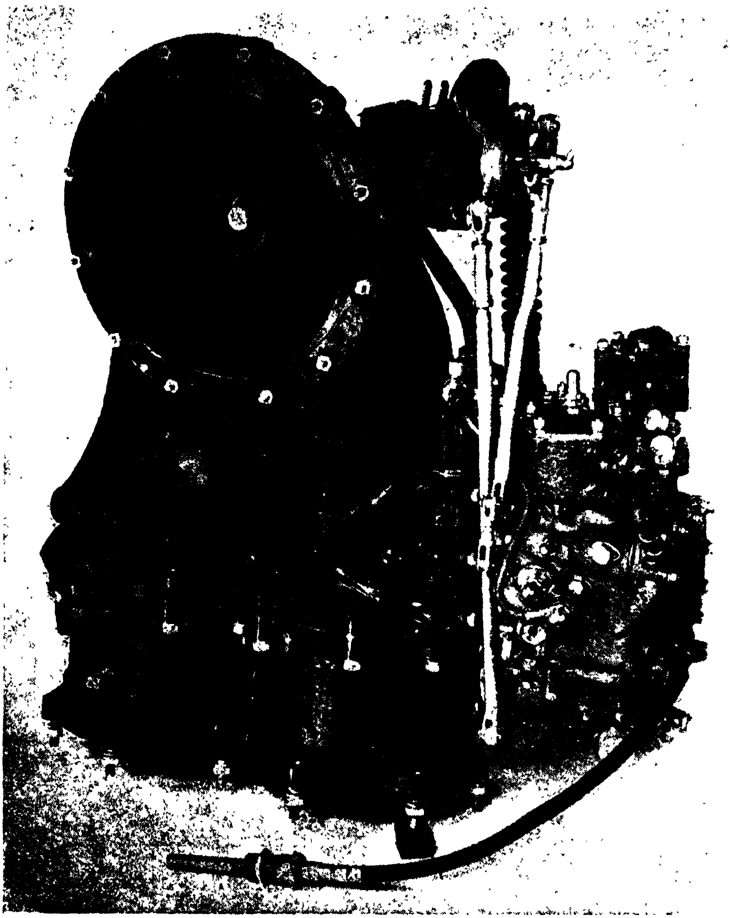
Both compartments of the vent valve diaphragm chamber shown in Fig. 102, are in communication with the front chamber of the pressure regulating unit, but the lower is normally sealed by the ball valve which is held on its seat by the square-sectional stop, the upper end of which is attached to the diaphragm.

The arrangement is such that for pressures under 5 lb. per sq. in. the spring will urge the diaphragm upward, thus lifting the valve stop and allowing the ball valve to be released. Any air or vapour present will be driven past the valve into the lower compartment and thence back to the tank by an external pipe.

On discharge of all air or vapour, the fuel will be on each side of the diaphragm, but the inlet to the lower compartment is restricted on account of the ball valve, so that when fuel only is pumped the pressure in the upper compartment exceeds that in the lower. Under these conditions the diaphragm and stop are forced down thus seating the ball valve.

The travel of the ball valve is initially adjusted by the makers of the injector (by means of an adjusting screw), so that sufficient restriction to the flow of fuel is established to close the valve, after permitting the escape of air.

Fuel Control Above the Full Throttle Height.—The boost control fitted to the Hobson-R.A.E. injector exercises control of the actual throttle valve similarly to that described for the float carburettor (page 132). As explained previously however, the boost capsule stack in the injector is also attached to the main fuel metering valve so that for any given boost pressure there is a definite orifice area, and conversely—for a given orifice area there is associated a definite boost pressure. The boost pressure selected by operation of the pilots throttle lever, e.g., cruising or rated, can only be maintained however, up to the full throttle height of the engine. Above this height, with full engine throttle, the boost pressure will decrease due to decreasing atmospheric pressure.



By courtesy of H. M. Hobson (Aircraft & Motor) Components Ltd.

FIGURE 104

THREE-QUARTER FRONT VIEW OF HOBSON R.A.E. INJECTOR TYPE B.I./N.5.4

(See fig. 12 for unit attached to engine.)

The orifice area is governed by the position of the pilots lever, so it is evident that above the full throttle height of the engine, the metering valve would continue to pass the quantity of fuel for a given boost although the actual boost was

decreasing. Any decrease in boost should be accompanied by a decrease in fuel supply, and in order that this condition should still be fulfilled above the full throttle height, a re-setting piston is fitted to the boost control unit. This piston, acting through a rod and lever, re-positions the metering valve to provide the necessary decrease in fuel according to the actual boost pressure between the full throttle height and the aircraft "ceiling."

The resetting piston is contained in a separate chamber, and is fed with pressure oil in the same sense as the boost servo piston and from the same oil valve. It is spring-loaded upward against a stop and is maintained in this position up to the full throttle height as the oil pressure on its upper side is insufficient to overcome the spring-loading. (Note that Fig. 102 shows slow running conditions, and that in flight pressure oil will be acting on top of both the boost servo and resetting piston.

At the full throttle height the boost servo piston will be at the end of its stroke, and above this height the pressure oil from the servo valve gradually increases on the resetting piston until it overcomes the spring-loading. When this occurs, the piston and its attached rod move downwards and through the medium of a link, lowers the metering valve and the boost capsule assembly. The capsule assembly pulls down the servo valve until the oil ports are approaching cut-off, which action arrests the resetting piston. Under these conditions the piston will have repositioned the main metering valve to pass fuel in accordance with the reduced boost pressure.

The general description given of the various units of the Hobson-R.A.E. Injector are mainly related to the type fitted to "Bristol" engines. The principle of the Injector is the same on other types but the various details are modified to conform to requirements of the particular engines of other manufacture.

From the details given it will be appreciated that the Master Control Injector is a precision instrument of the highest order, and its development, manufacture and successful

operation, represents another notable achievement in the field of British aero engineering.

It is interesting to note that with the injection carburettor there is considerable latitude in the positioning of the engine air intake which can now be placed in the position most advantageous for engine operation and installation. In this respect the rear view of the "Bristol" Centaurus 130 (Fig. 21) is of particular interest, as the double-entry air intakes to the supercharger can be clearly seen to port and starboard—a most unconventional position when considered in relation to normal carburettors.

The S.U. Type 601 *Single Point Fuel Injection Pump.*—This injector, manufactured by The S.U. Carburetter Co. Ltd., comprises a positive-displacement plunger pump of variable stroke driven by the engine at a fixed proportion of crankshaft speed.

The stroke of the plungers, which in conjunction with the speed governs the fuel delivery of the pump, is varied by control gear sensitive to variations in boost pressure, induction pipe temperature and the atmospheric or the exhaust back pressure.

The complete assembly consists of (1) the fuel feed pump, (2) the plunger or metering pump, (3) the hydraulic servo, (4) the temperature control capsule and boost diaphragm assembly and control spring, and (5) the variable leverage mechanism, these components being diagramatically illustrated in Figs. 105 to 107.

The gear feed pump, driven from the engine as shown (Fig. 105), draws, or is supplied with, fuel from the tank, which it delivers to the outlet "Fuel Supply to De-Aerator" by the internal passage indicated. The pressure rise across the pump is governed by the valve (7) which connects the pump inlet and delivery passages, the spring-loading being set to maintain a rise of approximately 6 lb. per sq. in.

Fuel, still at 6 lb./sq. in. pressure, delivered from the deaerator is then fed to the metering pump via a valve member (20), mounted on an eccentric formed at the end of the rotating shaft (16). The face of this valve is recessed in the centre

to provide a passage by means of which fuel can enter the plunger bores when these are uncovered by the circular "land" which forms the working face. The throw of the eccentric and its relation to the inclined or "Z" shaft (15) is such that when a plunger is on its induction stroke, the plunger bore is placed in communication with the valve recess and, when on delivery, in communication with the space contained within the valve cover (22) into which the fuel is delivered and from which it passes to the outlet union "Fuel Supply to Injector."

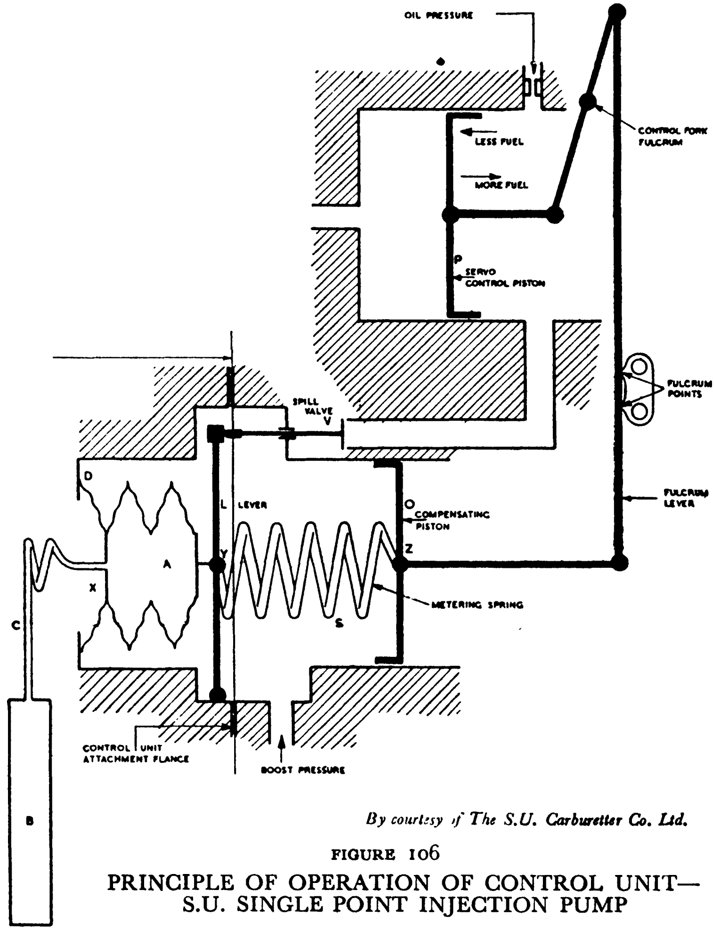
The Plunger Pump.—The equally spaced axially disposed plungers (9), working in bores formed in the block (10), have spherical ends which abut upon the flat face of the hemispherical wobble plate (11). Continuous contact between these members is maintained through the springs (12).

Reciprocation of the plungers is effected by the wobbling motion of plate (11), this motion being derived as follows:

The wobble plate, located within a spherical seating (13), is formed with a spherical recess in its bore, which houses a member (14) of spherical external form. The cylindrical bore of (14) is slidably mounted upon the oblique journal member (15), known as the "Z" shaft, which is itself slidably mounted upon the splined main shaft (16). The right hand extremity of the "Z" shaft has a grooved concentric portion engaged by trunnion block (17). The drive for the main shaft is taken from the splined bore of the fuel feed pump driving gear.

The geometrical centre (Q) of the hemispherical surface of the wobble plate lies upon the axis of the main shaft and (P), that of the member (14), upon the axis of the "Z" shaft. From the illustration it will be seen that (P) is displaced from the axis of the main shaft by the amount d, so that on rotation of the shaft, point P will describe a circle of radius d and, due to the spherical freedom of member (14), will impart a wobbling motion to plate (11) about the point Q. This wobbling imparts reciprocation to the plungers (9).

It will be clear that the amplitude of this reciprocation is proportional to the radius d—this in turn being dependent upon the position of the "Z" shaft. As the "Z" shaft is



By courtesy of The S.U. Carburetter Co. Ltd.

FIGURE 106

PRINCIPLE OF OPERATION OF CONTROL UNIT—
S.U. SINGLE POINT INJECTION PUMP

A—Four steel diaphragms forming a "bellows" connected to thermometric bulb "B" by a flexible tube " C." With diaphragm " D " they form the complete sensitive control element or " stack."
B.—Thermometric bulb mounted in induction tract.
C.—Capillary tube arranged to permit movement of point " X."
D.—Beryllium copper diaphragm, exposed externally to atmospheric pressure and internally to boost pressure, and supporting " Bellows A."
L.—Lever operating spill valve " V " and connected to " Bellows A " and compensating Spring " S " at " Y."
O.—Compensating piston. P.—Servo control piston.
S.—Metering spring, connected to piston "O" at point "Z."
V.—Spill valve. X.—Point of attachment of " D " and " C " to "A."
Y.—Point of attachment of "A" and " S " to " L."
Z.—Point of attachment of " S " to " O."

slidably mounted on the main shaft it can be positioned by means of the trunnion block (17) and its associated mechanism. If for example it is moved to the right hand extremity of its travel, the radius d will so diminish that point P finally coincides with the axis of the main shaft and under these conditions no movement of the wobble plate will occur. The pump will then be at its zero stroke position.

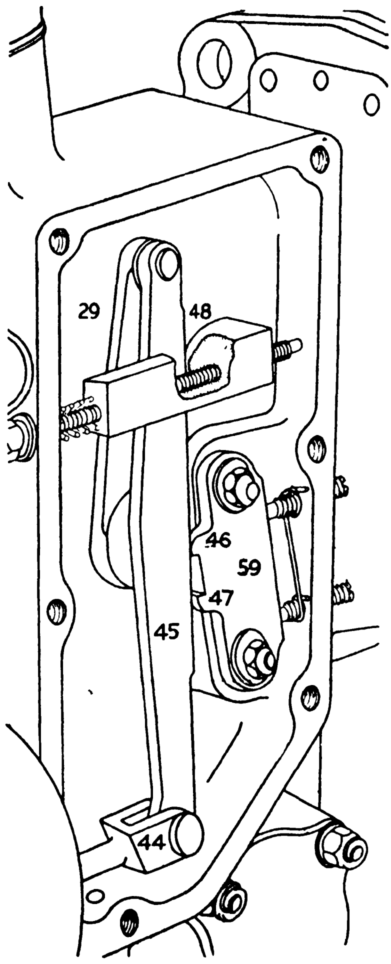
In this manner the stroke of the plungers and therefore the output of the metering component of the pump may be varied from zero to a maximum by anti-clockwise rotation of the control shaft (19).

The Hydraulic Servo.—Movement of the stroke varying mechanism is dependent upon the position of an oil servo piston (27), whose piston rod is yoked to the "Z" shaft trunnion as shown by Fig. 105. The fork piece member (28) is splined to the control shaft, partial rotation of which will move the "Z" shaft and piston in opposite directions.

Oil from the engine is supplied via a restrictor to the interior of the main casing, the only exit from which is via passage (26) and valve (25). With this valve open, oil can pass to the head of the servo piston, through the hollow bore of its rod and the passages indicated, back to the engine sump.

Assuming an anti-clockwise torque applied to the control shaft and valve (25) closed, oil pressure inside the casing will act on the underside of the servo piston, causing it to move to the left, thereby rotating the control shaft clockwise. At the same time the "Z" shaft will be moved to the right, so diminishing the stroke of the plungers.

If now the valve is permitted to open, the oil pressure will be reduced to approximately atmospheric (since the restrictor is small in comparison with the other passages), and the mechanism will be free to move under the influence of the torque applied to the control shaft. It will be evident therefore, that if an adequate anti-clockwise torque be constantly applied to the control shaft, the movement of the plunger stroke-varying mechanism in either direction is dependent upon the variation in loading of valve (25). This variation is



By courtesy of The S.U. Carburetter Co. Ltd.

FIGURE 107

LEVER MECHANISM, S.U. SINGLE POINT INJECTION PUMP

applied via tappet (30) by means of the temperature control capsule and boost diaphragm assembly.

Capsule and Diaphragm Assembly.—Fig. 106 shows this assembly diagrammatically, together with the metering control spring, boost compensating piston and associated control lever mechanism. The capsule assembly, metering spring and piston, are contained in a circular compartment on the side of the plunger block casing, while the lever mechanism is separately housed in a casing of rectangular form cast on the side of the main casing (Fig. 107).

The upturned control arm (29) which is formed on the end of control shaft (19) is indirectly affected by changes in the length of the capsule stack through the medium of lever (45), pushrod (44), boost piston (O), and metering spring (S).

As shown in Fig. 106, the internal pressure of capsule stack A is determined by that of the temperature bulb B, both together with the connecting capillary being hermetically sealed and filled with dry nitrogen at normal atmospheric pressure at 15°C.

Diaphragm D is exposed on its inner surface to atmospheric pressure (or exhaust back pressure in the case of a turbo blown engine), while the outer surfaces of both A and D are subject to boost pressure. The effective area of the stack D sensitive to atmospheric pressure is one-sixth of the total stack area reacting to boost pressure, i.e., the altitude reaction is one-sixth of the boost reaction.

The capsule stack is attached to a spring steel lever L at point Y, the latter also providing attachment for the metering spring S. The end of the lever carries the tappet (30) which operates on the oil servo valve (25) previously mentioned. Spring S is attached to the compensating or boost piston O at point Z. Piston O is to avoid the necessity of using a metering spring of the considerable strength required to move the plunger pump mechanism via the lever system. Under high boost conditions, the pressure acting on the piston provides the motive power, while for negative boost it will assist in compressing the spring.

Control Action.—The forces acting upon the pressure sensitive system are as follows:—

1. Those acting to the right, (a) initial set-up load exerted mechanically by the capsule stack, (b) the gas load inside the stack, (c) atmospheric, or exhaust back pressure.

2. Those acting to the left, (a) boost pressure, (b) mechanical load exerted by left hand extremity of metering spring.

If the forces acting to the right exceeds those acting to the left then lever L will apply a load to the tappet which will close the oil servo valve V.

As already detailed this will result in a build-up of oil pressure within the main pump casing and on the right hand side of the servo piston P which, being displaced to the left, will move the " Z " shaft to the right thereby reducing the plunger stroke and the fuel delivery.

As the control fork member linking the servo piston rod and " Z " shaft trunnions is splined to the control shaft (19), this movement will simultaneously cause clockwise rotation of the shaft, which, being communicated to lever (29), and fulcrum lever (45) rocking about the fulcrum (46), causes the compensating piston to move left and the metering spring to be further compressed. (It was assumed above that the forces acting to the right predominated, thus compressing the metering spring). This extra compression will continue until the reaction upon the capsule assembly is sufficient to balance exactly the forces acting to the right.

When this occurs, the load applied by the tappet to the valve V will be relieved, thus allowing it to unseat and release oil pressure. This reduction in pressure will continue until the pressure difference acting across the servo piston and applied to the piston area, is just sufficient to support, via the linkage, the load exerted by the right hand or movable end of the metering spring, when the whole mechanism will be in balance. If, for example, the reaction of the metering spring upon the pressure sensitive capsule assembly becomes slightly excessive, the load on valve V will be further reduced, permitting the pressure drop across the servo piston to be decreased to an extent that cannot support the reaction of the free end of the

TABLE 3.

CHANGES OF CONDITION WHICH NECESSITATE INCREASED FUEL DELIVERY

Change of Condition	Direction and change of stack reaction at point 'Y'	Effect on Spill Valve 'V'	Direction of movement of Servo Piston 'P'	Effect on fuel delivery	Direction of movement of compensating Piston 'O' and Point of Metering Spring Attachment 'Z'	Effect on Metering Spring 'S'	Direction and final 'change of Metering' Spring reaction at point 'Y'	
1 lb./sq. in. Boost increase	1.2 lb. <——	Opens	——>	Increases	——>	Extended	1.2 lb. ——>	Thus balancing the change of Stack Reaction and bringing it to its approx. constant control length.
1 lb./sq. in. Atmospheric Pressure Decrease	0.2 lb. <——	Opens	——>	Increases	——>	Extended	0.2 lb. ——>	
1°C. Drop in Charge Temperature	0.051 lb. <—	Opens	——>	Increases	——>	Extended	0.051 lb. —>	

Conversely, changes of Boost Pressure, Atmospheric Pressure or Charge Temperature in the opposite directions to those shewn above produce effects opposite to those indicated.

metering spring. The spring will thus extend, displacing the mechanism until its load on the capsule assembly has diminished sufficiently to cause the oil valve to regain its former position.

It will be seen, therefore, that any given combination of values of boost pressure, induction temperature, and atmospheric pressure, will result in some definite position of the free end of the metering spring and, in consequence, some definite " Z " shaft position. This results in some definite plunger stroke, i.e., the quantity of fuel displaced by the pump per revolution.

Table III indicates the effect of changes of condition which necessitate increased fuel delivery.

Variable Leverage Mechanism.—As indicated in Fig. 107, the fulcrum lever (45) is provided with a succession of vertically separated fulcrum points, (48), (46), and (47), against which its right hand edge abuts successively. The leverage of the fulcrum lever, or the ratio between the movement of the stroke varying mechanism and that of the free end of the metering spring, is obviously dependent upon the particular fulcrum utilized, and this mechanism is employed to provide varying air/fuel ratios for particular conditions of engine operation.

If, for example, at some particular boost pressure a richening of the mixture is desired, at this pressure it can be arranged for the fulcrum lever to leave point (46) and to pivot on (47). This will increase the leverage so that any further movement of the free end of the metering spring will result in a relatively greater increment in stroke than formerly and consequently an increased fuel delivery. A similar device, pivot (48), is employed to afford an adjustable richening of the mixture during idling.

The cam plate (59) is initially adjustable in horizontal, vertical and angular direction to meet tuning adjustments while the pump is on test rig.

The Injector Valve.—Fuel delivered by the plunger pump is supplied to the single point injector valve situated at the entry to the supercharger.

Timed Injection.—Although single point injection is in current use, timed injection to the individual induction ports or cylinders, will probably be the ultimate system so that air only will be handled by the supercharger.

One outstanding virtue of the timed direct injection system is the possibility of delaying the commencement of fuel injection in order to provide complete air scavenging without loss of fuel.

S.U. timed injection pumps, of similar basic design to the single point described, have already been developed.

CHAPTER VI

The Gas Turbine

The development of practical gas turbines for aeronautical purposes has been the outstanding achievement of this era. So great has been, and will be, its influence, that it is no exaggeration to apply the term " revolutionary " with regard to the science of aeronautics.

Due to the necessary secrecy imposed during its development and the fact that the gas turbine was first associated with aircraft as a means of *jet* propulsion, the advantages of such units for aircraft power plants even for driving propellers, or as propeller-jet combinations, have been somewhat overshadowed.

Those more familiar with the piston engine will naturally ask " what is a gas turbine, how does it operate and what are its advantages ? " And this enquiry is dealt with in the text which follows:—

In brief, a gas turbine is a form of internal combustion engine in which induction, compression, power and exhaust is *continuously* effected solely by *rotary* motion. The emphasis is on " continuous " and " rotary " as in the turbine, combustion and power is continuous (in contrast to the three idle strokes of the 4-cycle engine), and work is applied and delivered without reciprocation such as characterizes the normal engine. (It is a " revolutionary " unit in the real sense !).

In the engine, air is continuously inducted, compressed and delivered to a combustion chamber or chambers by means of a centrifugal or axial compressor ; kerosene is injected into the chamber and ignited, the resulting expanded gases being delivered at high velocity to the blades of a turbine wheel, the wheel thereby being rapidly rotated. After passing across the blades the gases are discharged in the form of a high speed jet. The compressor and turbine wheel being

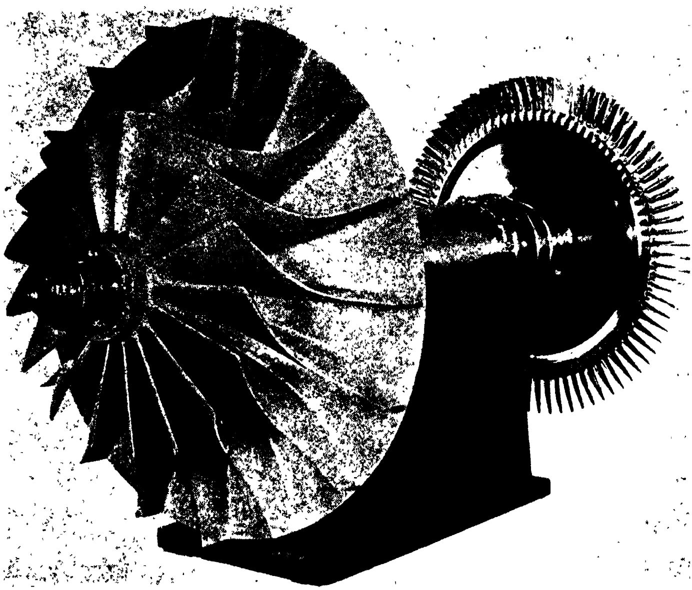
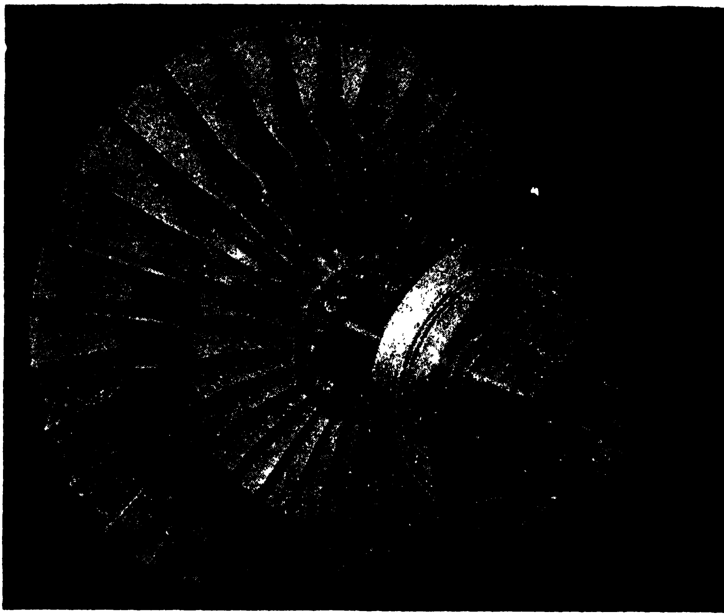


FIGURE 108 — *By courtesy of The De Havilland Aircraft Co. Ltd.*

ROTOR ASSEMBLY OF DE HAVILLAND GOBLIN 2 TURBO-JET

mounted on a common shaft, the power developed by the turbine is reduced by that required to drive the compressor. When used as a *jet* propulsive unit most of the turbine power is so absorbed, but for units intended to drive propellers, or for propeller-jet applications, the ratio is adjusted accordingly, as in these cases the turbine power is needed mostly for driving the propeller.

The basic construction of the rotor assembly of the centrifugal type turbo-compressor can be broadly ascertained from the views of the turbo-supercharger given by Figs. 87 and 88. In the actual turbine the impeller of the centrifugal compressor may be either single or double sided and is of aluminium alloy. The complete rotor assembly of the de Havilland Goblin 2 turbo-jet engine is illustrated in Fig. 108, and Fig. 109 shows the Rolls Royce Derwent 1 double-sided impeller.



By courtesy of Rolls-Royce Ltd.

FIGURE 109

ROLLS-ROYCE DERWENT 1, DOUBLE-SIDED IMPELLER

Turbines for Jet Propulsion.—In this application the propulsive force is obtained by the reaction of the small diameter high velocity exhaust gas stream, in conforming with that fundamental law of mechanics—to every action there is an equal and opposite reaction. Commonplace examples of this effect are, (1) the recoil of a gun when fired and (2) the back pressure due to a high velocity water jet which in fire-fighting equipment makes difficult the control of the nozzle.

The propulsive *efficiency* of propeller or jet system depends upon the relative velocities of the jet (or slipstream) and aircraft, and as the exhaust stream from the gas turbine issues at roughly 1,100 miles per hour, high speed aircraft are necessary to derive the full benefit of jet propulsion.

To obtain adequate thrust from a jet reaction, it will be realized that a great weight of air must be inducted and, by published values of sea level static performance, this is in the

neighbourhood of 1 lb. per second per 50 lb. thrust. As some of the present day turbines are operating in excess of 3,500 lb. thrust, equal to 70 lb. of air per second (867.4 cu. ft. at N.T.P.), the "breathing" capacity needs no emphasizing.

In flight, the high forward speed of the aircraft augments the air supply with a consequent increase in thrust. This is one of the great advantages of the system as the thrust power *increases* with forward speed even at constant R.P.M.

With regard to the great amount of air inducted by the compressor of the turbine, only about a quarter (by weight) is required for the actual combustion of the injected kerosene. The extra dilution air is required in order to keep down the temperature of combustion to a value at which the materials of construction can operate.

This excess air while lowering the thermal efficiency (heat input due to combustion of fuel/heat output equivalent of useful work) is not a real loss as it is expanded due to the heat of combustion and adds to the mass flow necessary for jet propulsion.

The gas turbine is essentially a heat engine, and the higher the temperature of combustion the greater is the expansion—which of course constitutes the "work done" part of the cycle. Just as increasing the compression ratio of the piston engine increases the thermal efficiency—thereby converting a larger portion of available heat to useful work—so does the compressor efficiency of the gas turbine. In this respect it is useful to note that the overall efficiency of a gas turbine increases with height owing to the fact that although the air inlet temperature decreases, the combustion temperature remains sensibly constant. This results in a greater temperature and pressure ratio across the engine—a relatively greater expansion—and more useful work. [Do not interpret this as meaning that there is an actual thrust increase with altitude. There is a fall in thrust power with increase in height due to the less weight of air consumed per second consequent upon the decreasing density. The improvement in heat cycle efficiency (with a constant air/fuel ratio), means that less fuel is required per lb. thrust, i.e., there is a decrease in specific

fuel consumption. For a given aircraft forward speed the thrust required decreases with increase in height due to the decrease in drag resulting from the diminished air density]. With continued research in metallurgy to provide materials having enhanced hot-strength characteristics, the maximum temperature of combustion can be increased with similar effect.

The exhaust temperature on sea level tests is about 550 deg.—600 deg. C. at the operating r.p.m. and internal temperatures will be much higher. R.p.m. vary with different types, the de Havilland Goblin II being 10,200 and the Rolls-Royce Derwent 14,700, these both being of the centrifugal compressor type. Axial compressors usually run at lower speeds.

Centrifugal and Axial Compressors.—Mention has been made previously that either of these types may be used for effecting the induction and compression of the air required, but at present the centrifugal type, due to its inherent simplicity, has been mostly employed in British gas turbines for jet propulsion. It is very similar in appearance to the light alloy impeller of piston engine superchargers and functions in a similar manner. Air drawn into the centre of the rapidly revolving impeller is discharged at high velocity at its periphery by the radial vanes and enters a duct of increasing cross sectional area, the purpose of which is to increase the pressure at the expense of velocity. The impeller may be either single or double-sided, the actual choice being governed by several factors such as engine rotor speed, overall diameter, air entry facilities and the design of the aircraft. The de Havilland Goblin utilizes a single-sided and the Rolls-Royce Derwent, a double sided impeller.

The compression ratio (absolute delivery pressure to intake pressure), of the compressor is very important with regard to its own efficiency and that of the useful output of the turbine, and meticulous care is taken in the design of the entry ducting, shape of blades, and clearances to keep the ratio high, using only a single stage. In this connection it is informative to note that, prior to Air Commodore Whittle's work, the highest ratio obtained by a single stage centrifugal compressor

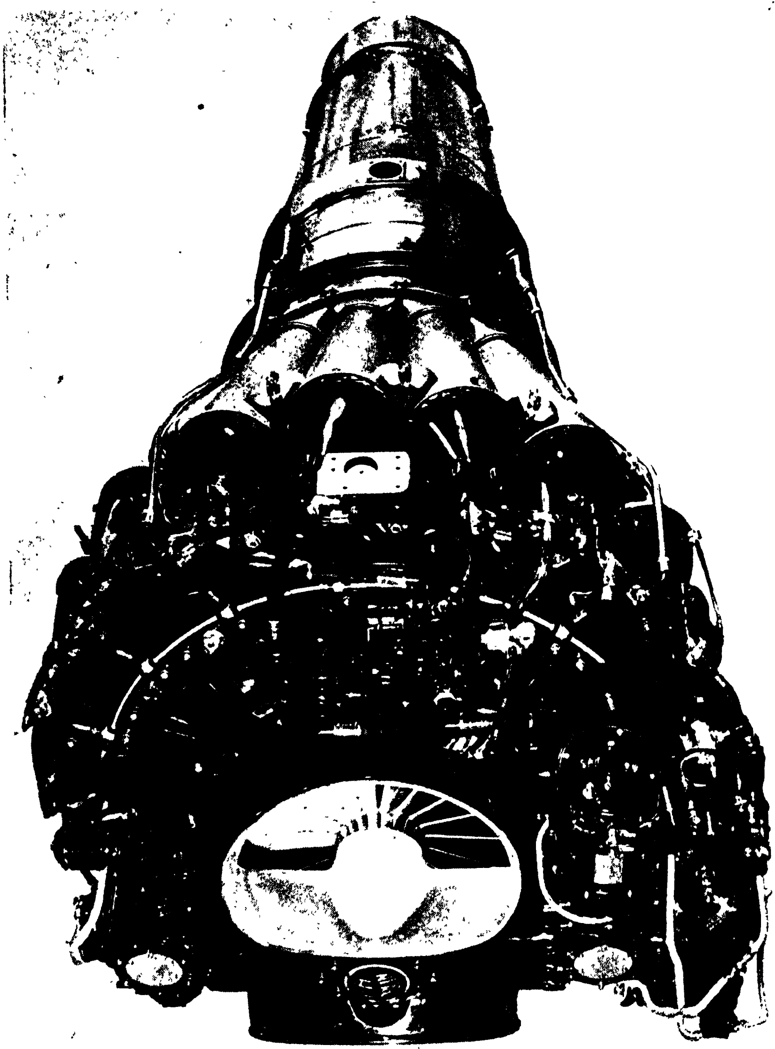
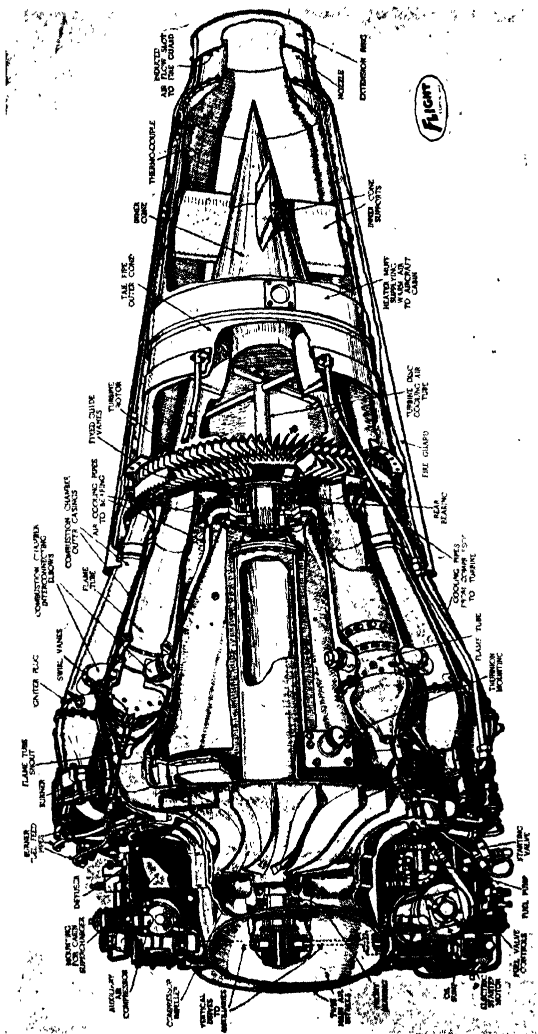


FIGURE 110 DE HAVILLAND GOBLIN 2 GAS TURBINE *By courtesy of The De Havilland Aircraft Co. Ltd.*



By courtesy of Flight

FIG. 111
CONSTRUCTIONAL DETAILS OF DE HAVILLAND GOBLIN 2

was about 2½ to 1. His work on the gas turbine raised the value to over 4 to 1. To increase the ratio further, two or more stages of compression are possible and although this is not current practice with centrifugal types, the axial compressors are invariably multi-stage.

The great advantage of the centrifugal compressor is the ease of production consequent upon its relatively simple form.

The axial compressor as its name implies effects compression of the air by axial translation and was the type most intensively developed for German gas turbines. In this country however, the possibilities of axial compressors were recognized by Dr. A. A. Griffiths as far back as 1926, and gas turbines of this type have been developed by the Metropolitan-Vickers Electrical Co., and Armstrong Siddeley Motors, Ltd.

The axial flow compressor consists of a rotor shaft carrying a disc or discs into the periphery of which are secured blades of aerofoil section. These blades run between rows of fixed "stator" vanes which redirect the air flow between stages of compression. The rotor is driven by the turbine wheel, and in action the bladed discs function in a similar manner to propellers, that is, they draw in and accelerate rearwards a mass of air. Being of aerofoil section, the blades are given "lift" in the direction of rotation.

Reference to Fig. 112 will give an indication of the difficulties involved in the design and production of multi-stage axial-flow compressors. Not only must the blading be aerodynamically correct for efficient operation, so must the clearances between rotor and stator blades.

The more difficult problems connected with this arrangement have resnlted in a slower rate of development than for the centrifugal compressor, but this is compensated, so it is claimed by greater operating efficiency. With multi-stages, a slower rotational speed is required for a given delivery, and the overall diameter of the engine is considerably less than when a centrifugal compressor is used.

The adiabatic* efficiency of a compressor is most important in order that the temperature of the air after compression is

* When a gas is compressed (or expanded) in such a manner, that heat is neither imparted or taken from it the compression (or expansion) is said to be adiabatic.

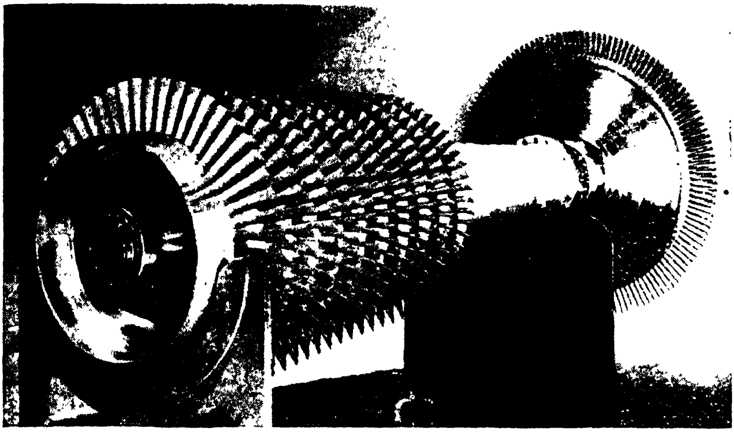


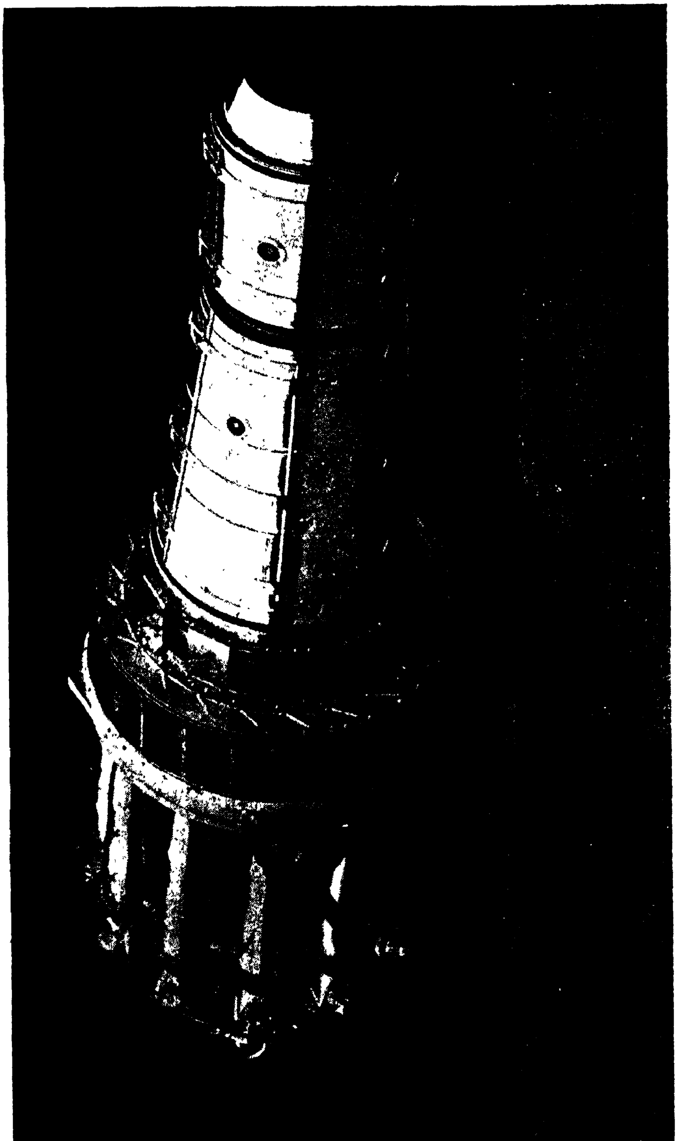
FIGURE 112 By courtesy of *Metropolitan-Vickers Electrical Co. Ltd.*

COMPLETE ROTOR ASSEMBLY OF METROVICK F 2/4 TURBO-JET ENGINE SHOWING TEN-STAGE AXIAL COMPRESSOR AND SINGLE-STAGE TURBINE

a maximum. (Compare for example the heating of a cycle pump when rapid compression is effected). The object is to convert as much as possible of the work done on the air to increasing its temperature and thus its internal energy. The higher the temperature after compression the more efficient is the heat cycle. The axial flow 14 stage compressor of the Armstrong Siddeley ASX engine (Fig. 113), established an adiabatic efficiency of 87 per cent.

The Tubine.—The axial flow turbine wheel needs all the careful design and manufacture that is bestowed on the compressor. Although the one cannot function without the other, it is the turbine which has to translate the energy of the expanding gas into useful work, and this while operating continuously at temperatures above 700 deg. C.

With continuous combustion and expansion the power developed by the turbine is prodigious as compared with the piston engine. The single-stage wheel of the Goblin develops about 6,000 b.h.p. and as stated previously, for jet propulsion units practically the whole of this power is needed to drive the air compressor. (This will give an indication of the power required



By courtesy of Armstrong Siddeley Motors Ltd.

FIGURE 113

ARMSTRONG-SIDDELEY ASX AXIAL COMPRESSOR-TYPE GAS TURBINE FOR JET PROPULSION

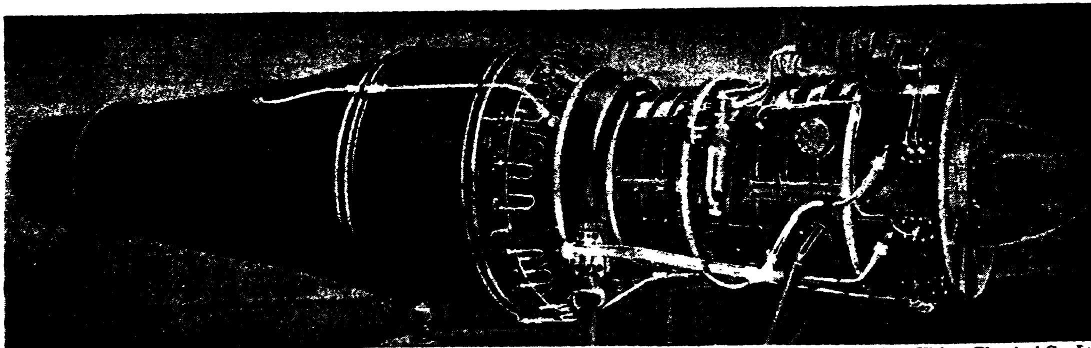


FIGURE 114 *By courtesy of Metropolitan-Vickers Electrical Co. Ltd.*

METROVICK (METROPOLITAN VICKERS) F 2/4 GAS TURBINE FOR JET PROPULSION

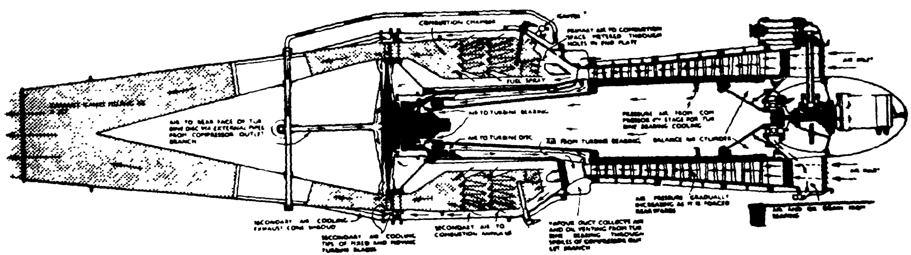


FIGURE 115 The Aeroplane *Copyright*

DIAGRAMMATIC SECTIONAL DRAWING OF METROVICK F 2/4 ENGINE.

to test compressors and turbines). The gas flow to the wheel blading is directed by means of stationary nozzle guide vanes.

Although a single-stage turbine is at present most common, some types developed have two stages, for example, the Armstrong Siddeley ASX, with 14 stages of axial air compression. The Metropolitan-Vickers F2 engine (the first British axial-compressor jet-propulsion turbine to power an aircraft in flight), originally had a nine-stage compressor and two turbine stages but in its later form (the F.2/4), has a ten-stage compressor and single stage turbine as illusrta'ed in Fig. 112.

Combustion.—From the compressor air is delivered through divergent passages to the combustion chamber or chambers into which the fuel is injected.

During the early development of the Whittle gas turbine, combustion problems were considerable and seriously interfered with progress. The intensity of combustion required was something far in advance of anything previously attempted, and many "trial and error" experiments were made. An idea of the complexity of the problem may be gathered from published values of fuel consumption. The de Havilland Goblin 2 gas turbine has a consumption of 1.23 lb. per hour per lb. thrust, and on the basis of the static thrust of 3,000 lb., the weight consumed per hour equals 3,690 lb. With complete combustion, and assuming a calorific value of 18,560 B.T.U./lb., the heat liberated is capable of raising to boiling point approximately 125 gallons of water *per second.*

Apart from the initial combustion research by Power Jets Ltd., and that by individual fuel and engine firms, a large programme was undertaken by J. Lucas Ltd., whose investigations and developments led particularly to the evolution of the "straight-through" combustion chambers as now used on most of the centrifugal compressor type of turbine.

To simulate the mass flow of air and pressure delivery conditions of the compressors of even the early gas turbines, "outsize" equipment was needed even for testing single combustion chambers. (Early Whittle type needed approximately 3 lb. of air per second at 40 lb. in.).

In order to cope with present-day and possible future developments, compressors each driven by a 2,250 h.p. electric motor are being installed—this for testing *single* combustion chambers !

Apart from the combustion *intensity* required, it must be uniform otherwise temperature variations across the gas flow may have an adverse effect on the strength of the turbine blading. There must be no sooting up of injection nozzles or combustion chambers and the materials must withstand the high temperatures developed and maintained.

In the first Whittle turbines, a single annular type of combustion chamber was used and various types of fuel vaporizers and spray nozzles, injecting both upstream and downstream, were tried with varying degrees of success (and failure). Multiple combustion chambers were then adopted and finally satisfactory combustion was achieved by the adoption of an atomized spray injection system developed by Mr. I. Lubbock of the Asiatic Petroleum Company (now Shell Petroleum Co., Ltd.). As the illustrations show, the multiple combustion chambers are a characteristic of most gas turbines.

The multiple casings visible are not the combustion tubes proper but are shells around the flame tubes, the annular space between the two being utilized for the main air supply from the compressor to the combustion chamber in " return-flow " combustion systems, and for secondary air in " straight-through " systems. In each case the air stream provides cooling for the chamber. On examination of the combustion chamber units it seems incredible that such light gauge sheet metal could function under the arduous conditions of operation.

In addition to the necessity for efficient combustion, the design of the chamber must be such that there is the minimum of pressure drop. For maximum expansion (and work done), the pressure delivery of the compressor must be maintained across the combustion system. As turbulence is necessary for efficient combustion, the swirl promoting vanes, etc., fitted for this purpose inevitably result in some pressure loss, of the order of 2 lb. per sq. in.

Return-Flow and Straight-through Systems.—These terms refer to the path taken by the air from the compressor into the combustion chambers. In the Whittle engine the fuel burners are at the rear (turbine end), of the chambers and the primary air for combustion is delivered to these via the annular space between the flame tube and outer casing. At the end of the casing the air is therefore " turned round " and reverses its direction of flow to enter the flame tube. After combustion the expanded gases are again swept round to the turbine wheel.

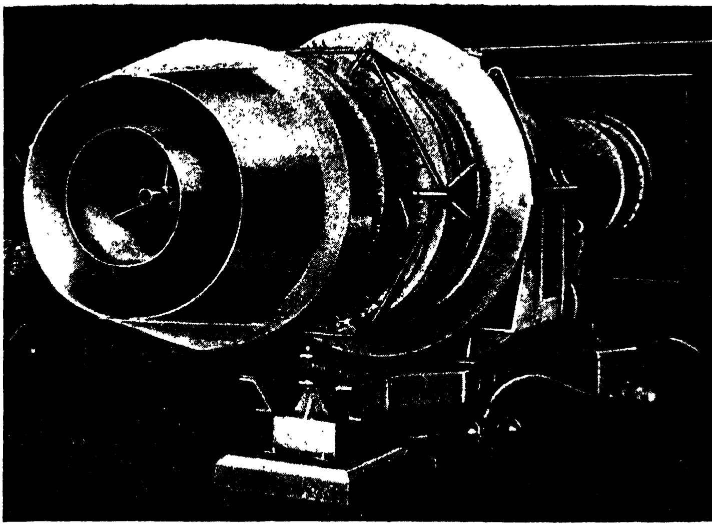
In subsequent developments of the basic Whittle engine by other manufacturers a straight-through flow from compressor to turbine was adopted. In this system the primary air for combustion is delivered directly to the burners which are at the front end and after combustion in the flame tube the gases are led directly to the turbine as shown in Fig. 111.

In both systems the secondary air is delivered into the flame tube via holes communicating with the annular surround.

Gas turbines with straight-through systems can usually be identified by the combustion chambers sloping from the compressor end to the turbine (see Fig. 110), and this certainly gives the engine a very elegant appearance.

For starting-up, an igniter plug is used in one chamber and, by means of interconnecting ducts, the flame from this lights up the others. Once combustion has started it is continuous.

Ducted Fan Thrust Augmentor.—This is a development for augmenting the thrust of the pure jet for speeds and altitudes below those most suitable for efficient operation of a turbo-jet, yet above those for optimum performance of a propeller drive, and can, therefore, be considered as a compromise between the two systems. It consists of a propeller type fan mounted in an annular duct surrounding the main turbine—hence the name "ducted fan." The fan may be driven in various ways, either by a turbine stage or by gearing from the rotor, and acting like a propeller, draws in extra air accelerating the mass rearwards through the annular duct thereby augmenting the thrust of the main jet stream. Fig. 116 shows the Metropolitan-Vickers F.2/1 axial-flow compressor type gas turbine with ducted fan thrust augmentor.



By courtesy of
FIGURE 116 *Metropolitan-Vickers Electrical Co. Ltd.*
METROVICK DUCTED FAN AUGMENTOR FITTED TO
F 2/1 TURBO-JET ENGINE

This, the first ducted fan augmentor, consists of a separate contra-rotation type turbine driven by the exhaust efflux of the main turbine. The first and third stages rotate in one direction while the second and fourth rotate the opposite way.

Mounted on the outer peripheries of these stages are rows of fan blades which entrain a large mass of free air and accelerate it rearwards through the annular jet shown.

Although the exit velocity of the main jet is reduced by the interposition of the augmentor turbine, the much larger mass of air accelerated by the augmentor (though at a lower discharge velocity than that of the main jet), gives a greater overall thrust for starting and at low forward flight speeds. This is achieved with a greatly reduced specific fuel consumption under these conditions.

Auxiliaries.—As may be seen from the illustrations, the various accessories necessary for engine operation are grouped around the forward ends of both types of turbine.

There is an electric starter motor, fuel pump, oil pumps, over-speed governor, air compressor, barostat, fuel and oil filters and various controlling devices such as a fuel distribution valve, automatic starting valve, and electrically energized switches.

No large volume of oil has to be carried; and in the case of the Goblin 2 about 12 pints are carried in a small sump at the bottom of the compressor front casing. Oil is supplied by a gear type pump to the accessories and drives and separate pumps deliver a metered supply to the front and rear rotor shaft bearings. This metered oil is a loss.

The high pressure fuel pump on this engine is rated at 650 gallons per hour at 800 lb. per sq. in. at 3,500 r.p.m., which corresponds to the maximum engine speed of 10,200 r.p.m. (the maximum burner pressure at take-off is 650 lb. per sq. in.). The fuel is delivered via a control box in which is a metering orifice, the area of which is controlled by a tapered needle valve operated by the pilots throttle lever.

As the weight of air consumed per minute decreases with altitude (due to decreased density), a corresponding reduction in fuel supply is necessary and this is automatically achieved by a barostat—this being analogous to the automatic mixture control of the piston engine carburettor.

For starting, igniter plugs are fitted in two combustion chambers (or at two points in the annular chamber of the axial-flow type), and by the interconnecting pipes the flame quickly lights up the remaining chambers.

Propeller Gas Turbines.—It has been mentioned previously that the efficiency and thrust of a gas turbine for jet propulsion increases with the forward speed and altitude, hence this type of propulsion is best suited for fast, high flying military aircraft. (In contrast, the propulsive efficiency of a propeller decreases with forward speed). The fuel comsumption is high, which though limiting the endurance, is not of such importance as when civil aircraft and long ranges are concerned.

There is, therefore, a range of forward speeds and altitudes at which the jet is neither an efficient nor an economical propulsive unit and to meet these requirements a turbine driving propeller combination is desirable. Due to the

comparatively low take-off speed of a jet-propelled aircraft, the thrust horse-power is low, and a propeller gives much higher thrust under the same conditions. As the pay-load of a civil aircraft is important it is evident that with high loads and slower take-off speeds, the maximum thrust required cannot be efficiently or economically obtained by jet propulsion alone.

For jet propulsion the function of the turbine is to drive as large a compressor as possible the latter absorbing practically the entire power output of the former. For propeller driving, however, the mass flow of air needed for the jet, is not required and the compressor needs to be the smallest possible that will supply the air necessary for the combustion of sufficient fuel to provide the greatest turbine drive. In this application the turbine must provide most of its power to drive the propeller. Apart from the general advantages of a gas turbine as a power unit (see page 190), it is particularly so for propeller work on account of the smoothness of drive. The cyclic torque variations of the piston engine are communicated to the propeller and impose fatigue stresses on the material. The blades must have adequate strength to cater for these and in consequence are heavier than necessary on account of aerodynamic stresses alone.

Heat Exchanger.—The generation of power in an internal combustion engine is dependent upon the expansion of the combusted air/fuel mixture, the expansion being a function of the rise in temperature. The thermal efficiency of an engine, i.e., its ability to convert heat into power, is reflected in its fuel consumption. High thermal efficiencies mean low fuel consumption for a given power and vice versa.

As the fuel consumption of a turbine propeller unit must compete with existing piston engines, it is essential to use any practical method that will increase its thermal efficiency, and for this purpose a heat exchanger is employed.

The heat exchanger is a device for preheating the air delivered by the compressor, and this is accomplished by utilizing the heat of the exhaust gases after they pass the turbine. These gases pass through the heat exchanger, and give up heat to the

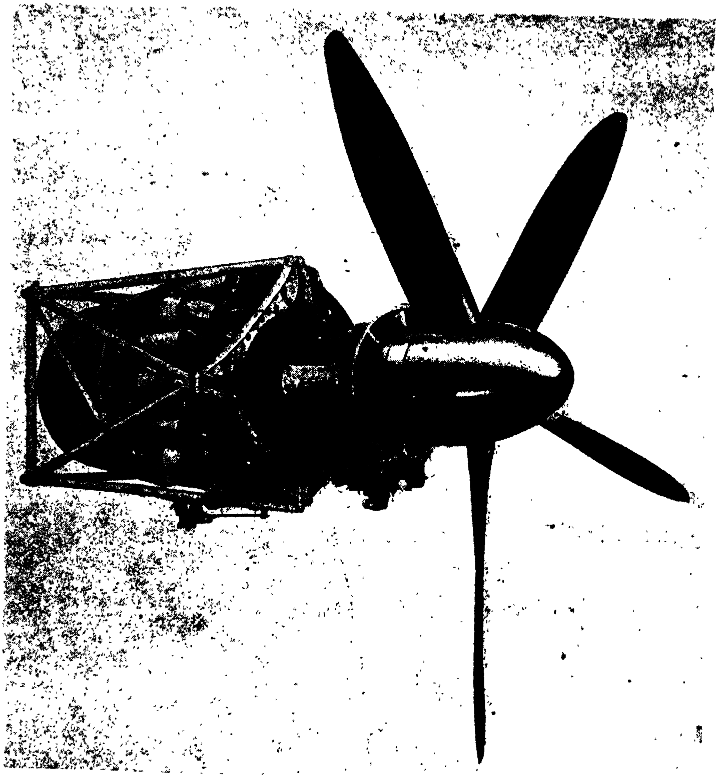


FIGURE 117 — *By courtesy of The Bristol Aeroplane Co. Ltd.*

"BRISTOL" THESEUS I PROPELLER GAS TURBINE

compressed air which is being delivered to the combustion chambers. This temperature rise before combustion improves the heat efficiency of the cycle. (Compare compression-ignition engine cycle and its high thermal efficiency).

The Bristol Propeller Gas Turbine.—To the pioneers of sleeve-valve development, the Bristol Aeroplane Company, another great achievement has to be credited, namely, the production of the first turbine-propeller unit of high power ***and low fuel consumption,*** using aviation kerosene, and designed specifically for installation in long-range aircraft—the Bristol Theseus I

of 2,000 h.p. (Fig. 117) having a dry weight of 2,310 lb. The sea level output is given as 1,950 s.h.p. plus 500 lb. static thrust.

Although this new unit is a radical change in conception from the famous line of sleeve-valve engines, yet exhaust turbo-superchargers were designed and fitted to "Bristol" engines as far back as 1924-5. In this connection, the illustrations of Figs. 87-88 are noteworthy, as they show the turbo unit as then constructed and flown successfully at over 30,000 ft.

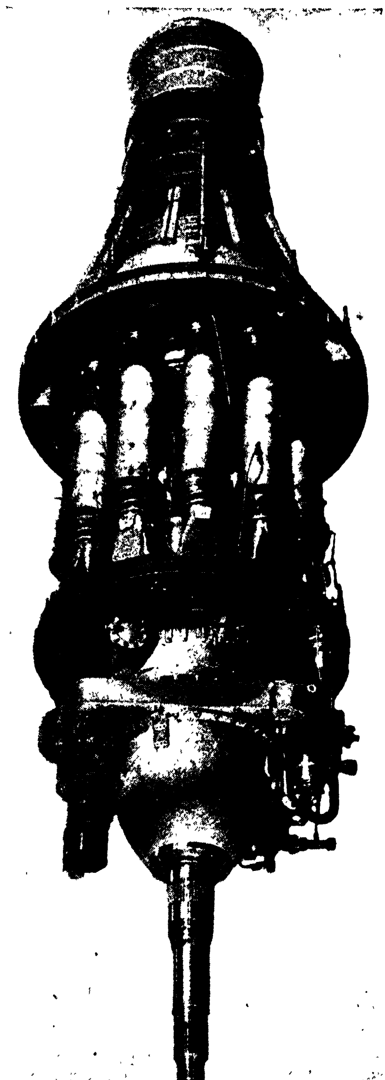
A turbo supercharger developed by D. Napier & Son Ltd. and fitted to the "Lion" engine was also successfully flown in this period (Fig. 89).

In addition, prior to 1939, turbo-blown versions of the sleeve-valve were envisaged in which, with high boost and back pressure, the powers of engine and exhaust turbo would be equal. At this stage the propeller (engine driven) could be interchanged with the blower (turbo-driven), i.e., a reciprocating engine with blower would act as a gas generator unit for a gas turbine driving a propeller. (An advantage of this arrangement is the improved fuel economy obtained due to the greater thermal efficiency of the piston engine. In this respect it is interesting to note that a two-stroke or compression-ignition engine with turbine has been proposed on account of the control of exhaust temperature which can be exercised by excess scavenging air. The exhaust temperature of normal four-stroke engines is rather high for existing turbine blading).

With this background, coupled with the subsequent developments in turbo-jet units the "Bristol" propeller gas turbine project was evolved.

For the Theseus I, the target of the designers was to produce a turbine which would have an overall fuel consumption comparable with that of a piston engine at 300 m.p.h., at a height of 20,000 ft. These conditions were postulated as the lowest speed and altitude at which the turbine could compete with convential engines; at higher speeds and altitudes turbine efficiency increases.

As gas turbines have no internal oil cooling or lubricating system and tankage comparable with that of the piston engine



By courtesy of Armstrong Siddeley Motors Ltd.

FIGURE 118

ARMSTRONG SIDDELEY PYTHON TURBINE WITH GEARING FOR CONTRA-ROTATING PROPELLERS

the designers concluded that if a fuel consumption within 5 to 10 per cent. above that of this engine could be obtained, then the propeller/turbine unit could compete successfully. This requirement was fixed as the full load condition as turbines are most efficient at full power and it was not necessary to provide for any other condition except that of cruising (for the turbine this is close to full power).

The Theseus I has a compound compressor consisting of a multi-stage axial-cum-centrifugal type (nine stage axial and single stage centifrugal), the annular air entry of which is around the propeller reduction gearing. The compressed air is delivered to the combustion chambers via a heat exchanger, the products of combustion passing to a stage turbine directly coupled to the compressor. After leaving this turbine the gases pass to a further *separate* single turbine stage which drives, via a forward extension shaft the propeller reduction gearing. From the second turbine the gases pass through the heat exchanger, where they give up some heat to the compressed air on its way to the combustion chambers. The exhaust gases are then finally discharged through a controllable nozzle, thus producing forward thrust.

A great feature of the above arrangement is the separate turbine stage drive for the propeller. As this is not connected with the compressor the propeller r.p.m. can be varied without affecting the overall turbine efficiency, thus enabling maximum thrust to be obtained. With a propeller directly coupled to the main turbine rotor, speed control could be effected by multi-ratio reduction gearing but only at the expense of complication and additional weight.

The most powerful turbine propeller unit of which particulars are available is the Armstrong Siddeley Python (Fig. 118), giving 1,150 lb. thrust + 3,670 s.h.p. at sea level. The engine, developed from the ASX turbo-jet previously mentioned, has reduction gearing for contra-rotating propellers.

A more recent addition to the Armstrong Siddeley range is the Mamba engine, a smaller unit designed as a propeller jet combination with axial flow compressor to produce 1,000 s.h.p. for sea level take-off plus 320 lb. static thrust. With cowling

the overall diameter of this compact unit is only 27 ins. and weight 750 lb.

Rolls-Royce engines have also been designed for propeller work so it is evident that the propeller-jet unit is being rapidly developed.

Advantages of the Gas Turbine.—For aeronautical use the advantages of any form of power unit have to be related to the particular conditions under which it must operate. For example, it is of little use to obtain the very minimum fuel consumption if that asset is accompanied by greatly increased weight which would nullify the fuel economy. In order that any type may have decided superiority there must be a combination of advantages that greatly outweigh any disadvantages.

The gas turbine, still in its infancy, does possess that balance of advantage for the following reasons.

1. Simplicity—as compared with the multitude of components needed for the conventional supercharged piston engine. The greater the number of mechanical devices the greater the complexity and possibility of failure. The inherent simplicity of the turbine makes development, design and production more speedy.

2. Weight/Power Ratio—The continuous combustion and high operating speeds combined with the low weight gives a ratio much below that of the piston engine. For the turbo-jet and equal powers, the turbine is approximately one third the weight of the conventional engine. (The higher fuel consumption of the turbine may offset this advantage under some conditions but it should be realized that the high flight speed of the turbo-jet will reduce the time of flight for a given distance and therefore the weight of fuel to be carried. In addition no large oil capacity is needed as required for a conventional engine).

3. Smoothness of running.—The torque variations of the piston engine induce additional stresses in its members and the unbalanced forces due to reciprocation set up vibratory forces which are communicated to the aircraft structure. The absence of torque variations and reciprocation gives an ideal smoothness of running to the turbine.

4. Propulsive efficiency of the turbo-jet increases with speed and height.

5. The ability to operate with simpler fuels.

6. Greater latitude in installation position with benefits of reduced drag.

7. The ability to be used for propeller drives as well as for jet propulsion.

8. Turbines can be designed for power outputs much in excess than those possible with reciprocating engines.

9. Cruising power can be near the full power without adversely affecting the specific fuel consumption.

EVENTS IN THE DEVELOPMENT OF BRITISH GAS TURBINES.

A. *Axial Compressor Types.*

1926-8 Dr. Griffiths at the Royal Aircraft Establishment put forward a theory of turbine design based on aerofoils. Tests made with aerofoils and single-stage compressor and turbine.

1929 Dr. Griffiths proposed gas turbine for propeller driving, utilizing contra-rotation and contra-flow principle (adjacent rows of blading rotate in opposite directions).

1936-8 Axial flow compressor built and tested at R.A.E.

1937 H. Constant at the R.A.E. proposed gas turbine driving a propeller for aircraft.

1938-40 Metropolitan-Vickers Electrical Company in conjunction with R.A.E. designed and built low pressure axial compressor driven by a high pressure turbine. Complete unit run in December, 1940. In 1939, C. A. Parsons Ltd., built and tested eight-stage axial compressor.

Other compressors built by the (British) General Electric Company to R.A.E. aerodynamic design. Experimental turbo-compressor as proposed by Dr. Griffiths in 1929, designed at R.A.E., built by Armstrong Siddeley Motors Ltd., and run in 1940. Rolls- Royce experiments with "Griffith" type turbo-compressor.

1940-3 Metropolitan-Vickers Electrical Company commenced work on axial-compressor gas turbine for jet propulsion—nine-stage compressor, single annular combustion chamber and two-stage turbine (F.2). Two of these engines in a Gloster F.9/40 made the first flight of a British axial-compressor gas turbine for jet propulsion in November, 1943. Further development on ten-stage compressor and single stage turbine with first ducted fan augmentor. Armstrong Siddeley Motors Ltd., built and tested 14 stage compressor and two-stage turbine unit (ASX). This engine also adapted for driving a propeller is known as the ASP. or the Python.

1945 Bristol Theseus I announced. Axial-cum-centrifugal type compressor driving separate turbines for compressor and propeller, with jet propulsion. (Note: Bristol Jupiter type engine with exhaust turbo-supercharger was flying in 1924-25).

B. *Centrifugal Compressor Types*

1928 Air Commodore Whittle (then Flight Cadet), wrote thesis in which was discussed the possibilities of jet propulsion and gas turbines for aircraft.

1930 Whittle applied for patent covering jet propulsion turbine.

1935 With Messrs. Williams and Tinling, a company named Power Jets Ltd., was formed to develop the gas turbine.

1936 Order for experimental engine placed with The British Thomson-Houston Company Ltd. (Combustion chamber by Laidlaw, Drew and Company).

1937 Testing of first engine.

1938 Testing of modified original engine. Another major reconstruction and series of tests.

1939 Air Ministry placed contract with Power Jets, Ltd., for flight engine and Gloster Aircraft Company for experimental aircraft E.29/39. Manufacture of flight engine undertaken by B.T.H. Co. Ltd.

1940-2 Rover Company commenced manufacture of Whittle gas turbine, and later developed engines (W2B23—prototype of the Welland) incorporating their own ideas, for installation in Gloster F.9/40—the prototype Meteor.

" Straight-through " combustion system incorporated—engine later developed by Rolls-Royce to Derwent class.

1941 The first flight engine (W.1), installed in Gloster E.28/39 for flight trials. First flight on May 15th. (During early taxi-ing tests another engine the W.1.X., was installed and the machine did actually leave the ground for a short hop).

(October, 1941—W.1.X. engine, and drawings of later model, sent to U.S.A. to initiate development at General Electric Company).

1941-5 Design, manufacture and testing of de Havilland H.1. Goblin (1941-2). First flight of Gloster Meteor with two Goblin engines (March, 1943). Initial trials of de Havilland Vampire powered by Goblin engine (September, 1943). (Prototype Lockheed Shooting Star powered by Goblins first flew January, 1944). January, 1945, Goblin passed official type Approval Test.

1942-5 Rolls-Royce Ltd., commence production of Whittle type engine, incorporating their ideas on blower, turbine and mechanical design. Took over from Rover Company the prototype Welland engine and developed to Derwent and Nene types. Modified Derwent to Trent class for experimental propeller driving.

The main events only have been given in the foregoing lists, which refer chiefly to complete engines. Much detail and experimental work was undertaken by other firms whose contributions have been previously discussed in the technical press. The work goes on !

De Havilland Goblin 2 Engine

Turbo-jet, single-sided single-stage centrifugal compressor, multiple combustion chamber, single-stage axial flow turbine.

Leading Particulars under Static Sea Level Conditions.

Maximum Thrust	3,000 lb. at 10,200 r.p.m.
Crusing Thrust	1,850 lb. at 8,700 r.p.m.
Specific Fuel Consumption	
Take-off	1.23 lb./hr./lb. thrust
Crusing	1.30 lb./hr./lb. thrust
Weight	1,550 lb.
Maximum diameter	49.85 in.
Air mass flow	60 lb./sec.
Total Air/fuel ratio	58 to 1
Temperature rise across compressor	150 deg. C.
Turbine inlet temperature ..	790 deg. C.
Jet Velocity	1,610 ft./sec.

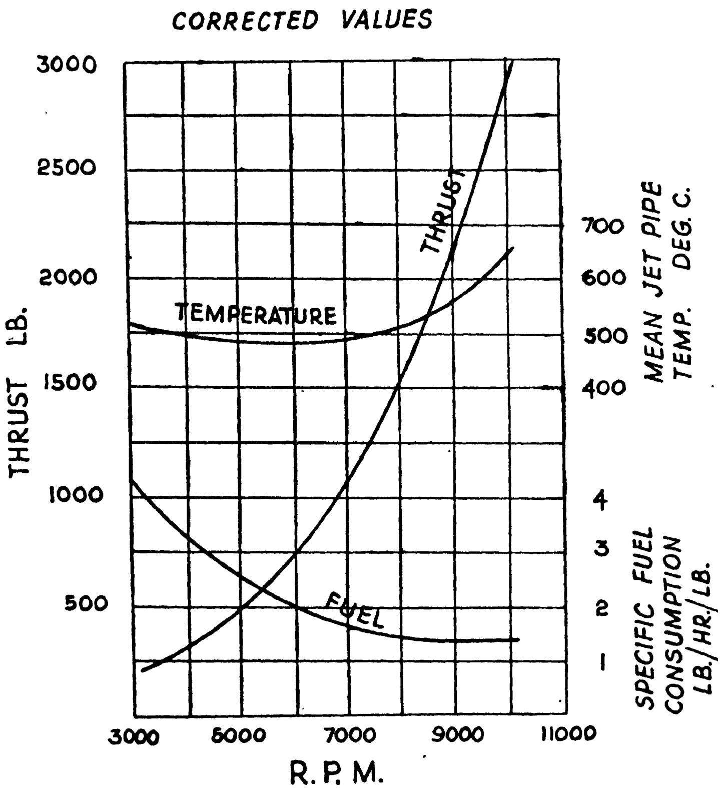


FIGURE 119 DE HAVILLAND GOBLIN 2 ENGINE PERFORMANCE

Metropolitan-Vickers F.2/4 Engine

Turbo-jet, ten-stage axial flow compressor, single annular type combustion chamber, single-stage axial flow turbine.

Leading Particulars under Static Sea Level Conditions

Maximum take-off thrust ..	3,500 lb. at 7,700 r.p.m.
Maximum climbing thrust ..	3,300 lb. at 7,545 r.p.m.
Maximum cruising thrust ..	3,000 lb. at 7,315 r.p.m.
Specific Fuel Consumption	
Take-off	1.05 lb./hr./lb. thrust
Cruising	1.00 lb./hr./lb. thrust
Weight	1,750 lb.
Maximum diameter	37·9 in.

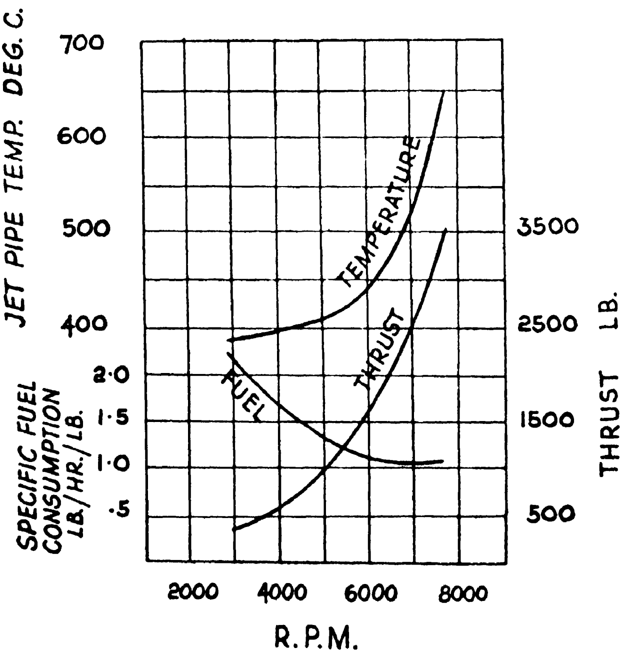


FIGURE 120

METROVICK F 2/4 ENGINE PERFORMANCE

TABLE 4.

SUMMARY OF PARTICULARS OF BRITISH GAS TURBINES.

Engine	Compressor	Output - Sea Level Static Conditions		R.P.M.	Dimensions		Dry Weight
					Dia.	Length	
		lb. thrust	S.H.P.		in.		lb.
A. Turbo-Jets							
Rolls-Royce Derwent I	Centrifugal	2,000	—	16,500	41.5	83.9	940
Armstrong Siddeley ASX.	Axial	2,600	—	8,000	42.0	167.0	1,900
de Havilland Goblin I	Centrifugal	2,700	—	10,000	49.8	100.5	1,520
de Havilland Goblin II	Centrifugal	3,000	—	10,200	49.8	100.5	1,560
Rolls-Royce Derwent V	Centrifugal	3,500	—	14,700	42.0	83.1	1,250
Metropolitan-Vickers F.2/4A	Axial	3,500	—	7,700	37.3	146.4	1,750
de Havilland Ghost	Centrifugal	5,000	—	—	53.0	127.0	1,950
Rolls-Royce Nene I	Centrifugal	5,000	—	12,300	49.5	96.8	1,630
B. Propeller Units							
Armstrong Siddeley Mamba	Axial	320	1,010	—	27.0	77.0	750
Bristol Theseus I	Axial and Centrifugal	500	1,950	8,200	48.0	112.0	2,310
Armstrong Siddeley Python	Axial	1,150	3,670	8,000	54.5	136.0	3,010

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